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NBS TECHNICAL NOTE 1018

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

An Assessment of the Backscatter Technique as a Means for Estimating Loss in Optical Waveguides

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t/ Technical note

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Issued February 1980

NATIONAL BUREAU OF STANDARDS TECHNICAL NOTE 1018

Nat. Bur. Stand. (U.S.), Tech. Note 1018, 88 pages (Feb. 1980)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1980

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

Stock No. 003-003-02160-1 Price $3.75 (Add 25 percent additional for other than U.S. mailing)

CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLE I. LIST OF SYMBOLS NOMENCLATURE AND UNITS

SYMBOL	NOMENCLATURE	UNITS
$A_1(n)$	Bulk absorption loss for n^{th} element for forward traveling pulse	
$A_2(n)$	Bulk absorption loss for n^{th} element for back traveling pulse	
$A_3(n)$	Total forward loss for n^{th} element = $A_1(n)+S_1(n)$	
$A_4(n)$	Total back loss for n^{th} element = $A_2(n)+S_2(n)$	
B	Detector bandwidth	Hz
$C_1(n)$	Capture fraction for n^{th} element	
$E_f(n)$	Energy of forward traveling unit input pulse at n^{th} element, measured at time $n\Delta T$	J
$E_b(n)$	Energy of back traveling pulse from n^{th} element measured at time $2n\Delta T$	J
F	Effective noise figure	
i_n	Noise current in detector	A
i_s	Signal current in detector	A
k	Assumed number of elements in waveguide model	
L_1	Direct (insertion, two-length, cut-back or conventional) attenuation	dB
L_2	Least-squares backscatter attenuation	dB

TABLE I. LIST OF SYMBOLS NOMENCLATURE AND UNITS (Continued)

L_3	Two-point backscatter attenuation	dB
L_4	Piecewise least-squares backscatter attenuation	dB
m	Dummy index for element in sampled pulse	
M	Assumed number of elements in input pulse. Also used to denote detector multiplication factor.	
n	Dummy index for element in waveguide model	
N_1	Core index of refraction on fiber axis	
N_2	Cladding index of refraction	
NA	Numerical aperature (see text). Not to be confused with the abbreviation N.A. for not applicable.	
$P_b(n)$	Average backscatter power at fiber input end measured at time $2n\Delta T$	W
$P_f(n)$	Average forward traveling pulse power measured at time $n\Delta T$	W
$P_i(m)$	Average power in input pulse measured at time $2m\Delta T$	W
q	Electronic charge	C
r	Correlation coefficient for least-squares fit	
R	Random number	
R_i	Detector responsivity	AW^{-1}

$S_1(n)$	Bulk scattering loss for n^{th} element for forward traveling pulse	
$S_2(n)$	Bulk scattering loss for n^{th} element for back traveling pulse	
S/N	Signal-to-noise ratio	dB
t	Time	s
v	Group velocity of pulse propagating in waveguide structure	ms^{-1}
X_o	Fiber length	m
α_1	Total distributed waveguide loss in forward direction = $\alpha_1' X_o$	
α_2	Total distributed waveguide loss in back direction = $\alpha_2' X_o$	
α_s	Rayleigh scattering loss = $\alpha_s' X_o$	
α_1'	Distributed waveguide loss per unit length in forward direction	m^{-1}
α_2'	Distributed waveguide loss per unit length in back direction	m^{-1}
α_s'	Rayleigh scattering loss per unit length	m^{-1}
ΔT	One way transit time of a narrow pulse across a differential element	s
Δx	Length of differential element in waveguide model	m

AN ASSESSMENT OF THE BACKSCATTER TECHNIQUE AS A MEANS FOR ESTIMATING LOSS IN OPTICAL WAVEGUIDES

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This technical note addresses some of the problems associated with determining the accuracy of the backscatter technique as it is applied to the estimation of attenuation in optical waveguides. The basic theoretical assumptions involved in optical time domain reflectometry are reviewed; the effect on calculated loss values resulting from a departure from these assumptions is then examined. The approach taken is to employ computer modeling of the various scattering and other loss mechanisms using the bulk material properties of optical fibers. Computer responses permit a numerical comparison between the direct (insertion) method of measuring attenuation and several methods of estimating attenuation from analysis of backscatter data. Numerous examples are given of physical effects which can produce discrepancies in attenuation values calculated from backscatter signals. Also, some experimental comparisons are made between backscatter-derived and directly measured attenuation values in step and graded-index optical waveguides. Finally, the conditions necessary for good agreement between the direct and backscatter methods are discussed and suggestions for minimizing these errors are made.

Key Words: Backscattering; fiber attenuation; fiber loss; fiber scattering; optical time domain reflectometry; Rayleigh scattering.

1. INTRODUCTION

There are basically two different experimental techniques for the determination of attenuation in optical waveguides. The direct, or insertion, method measures the actual transmitted power loss of a long length of fiber. The second method involves the calculation of attenuation from principles of optical time domain reflectometry (OTDR), and is based on the Rayleigh backscatter impulse response of an optical fiber. It has been observed experimentally that the two approaches do not always exactly agree. It is the purpose of this report to examine, by means of computer modeling, some of the errors and measurement problems associated with estimating attenuation from OTDR.

The attenuation of an optical waveguide at a given wavelength, between

two cross-sections 0 and 1 separated by a length of fiber X_1 is usually defined as:

$$L_1 = 10 \log \left[\frac{P_f(0)}{P_f(1)}\right] \text{ dB.} \qquad (1\text{-}1)$$

where P_f (0) is the optical power traversing cross-section 0, and P_f (1) is the power traversing cross-section 1. To help insure that the conditions of excitation remain constant for the two required measurements, the fiber is cut near the input end and P_f (0) is the measured power output of this short length of fiber. We will refer to L_1 measured in this way as the direct attenuation; also referred to as the insertion, two-length, or cut-back method.[1] We will also include as part of the attenuation of the fiber such environmentally-induced effects as fractures and radiation at micro-bends even though, strictly speaking, these are not intrinsic properties of the fiber in question. In general, the attenuation measured according to the prescription of eq (1.1) will be dependent on the exact optical power launching conditions [1,2] and, consequently, fiber length. Nevertheless, it is common practice to characterize fibers in terms of a loss rate, or loss per unit length given by L_1/X_1. Most commercial fibers are specified in this way with units of dB/km.

The backscatter technique for estimating attenuation in fibers was suggested by Kapron et al. [3] and implemented by Barnoski [4] and Personick [5]. Here, loss is determined from an experimental fit to the exponential decrease as a function of time of the Rayleigh-backscatter power from a fiber excited by a short pulse of radiation. The usual method reported in the literature [4-6] is to use a least-squares curve-fitting routine to fit an exponential function to the experimental backscatter signal which is a function of time. This gives a "best fit" decay constant which is simply related to the attenuation under certain restrictive conditions. Where the fiber consists of two or more regions of different, but uniform, loss characteristics (such as two dissimilar fibers spliced together) then a piecewise least-squares fitting can be done over each region separately. The backscatter power impulse response can be converted to a length dependence of the form

[1] The expression "insertion loss method" has been used to refer to the technique whereby the power P_f (0) measured through a short length of fiber, and the power P_f (1) through the test fiber are made independently. In each case adjustments are made in the launch conditions to maximize power throughput. This procedure avoids repeatedly cutting the fiber, but introduces the possibility of errors due to lack of alignment precision. In this note we will make no distinction between "direct" and "insertion" measurements.

$P_b(x) = P_b(0)\ \exp\ (-2\langle\alpha\rangle X_1)$. This is shown later to give

$$L_2 = 5\ (\log e)\ \langle\alpha\rangle X_1 \mathrm{dB} \tag{1-2}$$

where $\langle\alpha\rangle$ is the best fit (in the least squares sense) to the exponential decay and L_2 is our designation for fiber attenuation measured from a least squares fit. It is shown in sections 3 and 4 that the two methods for determining loss are identical for fibers that are uniform throughout their length and have identical properties in the forward and back directions. If these conditions are not satisfied then in general the results of the two approaches do not agree.

There are other data reduction techniques for estimating fiber attentuation from the backscatter signal. One of these we will examine in detail and refer to the two-point method. This attenuation, denoted by L_3 is given by the expression

$$L_3 = 5\ \log \frac{P_b(0)}{P_b(1)}\ \mathrm{dB} \tag{1-3}$$

where P_b (1) is backscatter signal from the cross-section labeled 1 and P_b (0) is the backscatter signal from the input end at x = 0. We shall see that, under some circumstances, this approach gives closer agreement with the direct attenuation than is obtained from least-squares curve fitting.

Although the direct method is generally preferred for loss measurements, the backscatter technique has definite advantages in certain applications. For example, the power level, and loss, in the fiber can be determined as a function of length. Mode coupling effects may be observed. Regions of high absorption loss or scattering loss can be identified and located nondestructively as a function of position along the fiber. The fiber does not need to be cut to determine loss. Another important application is in field measurements where there is access to only one end of the fiber. Also, this technique provides a convenient way to measure the additional loss due to splices and devices inserted into the optical waveguide such as couplers and connectors.

In this report we will assume that scattering in the waveguide is a linear function of pulse power. In fact, non-linear effects such as stimulated Raman and stimulated Brillouin scattering have been observed in some single mode fibers. The threshold for these effects has been calculated [6]. Experimental evidence [7] indicates that 2 kW peak power can be

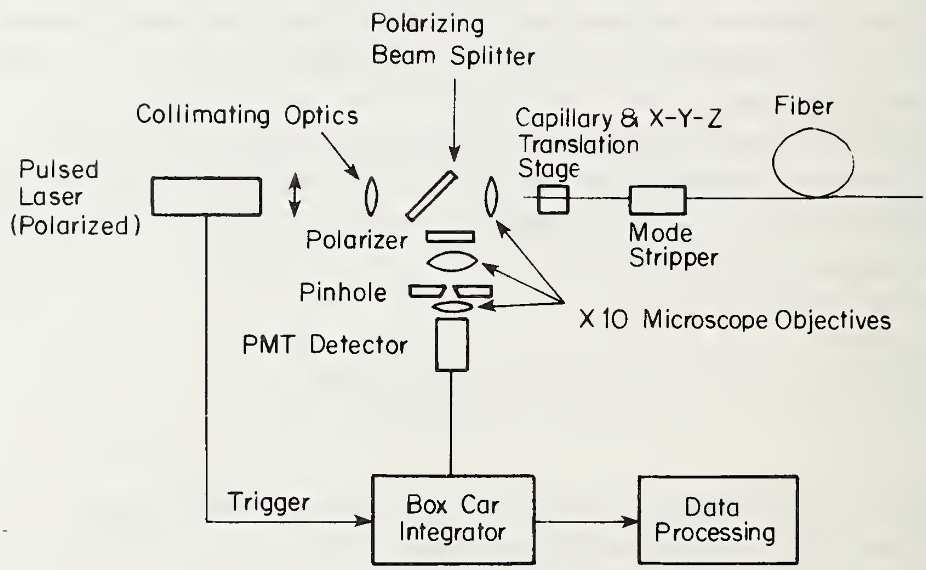


Figure 1. Experimental apparatus for backscatter measurements. Polarization is indicated by arrows.

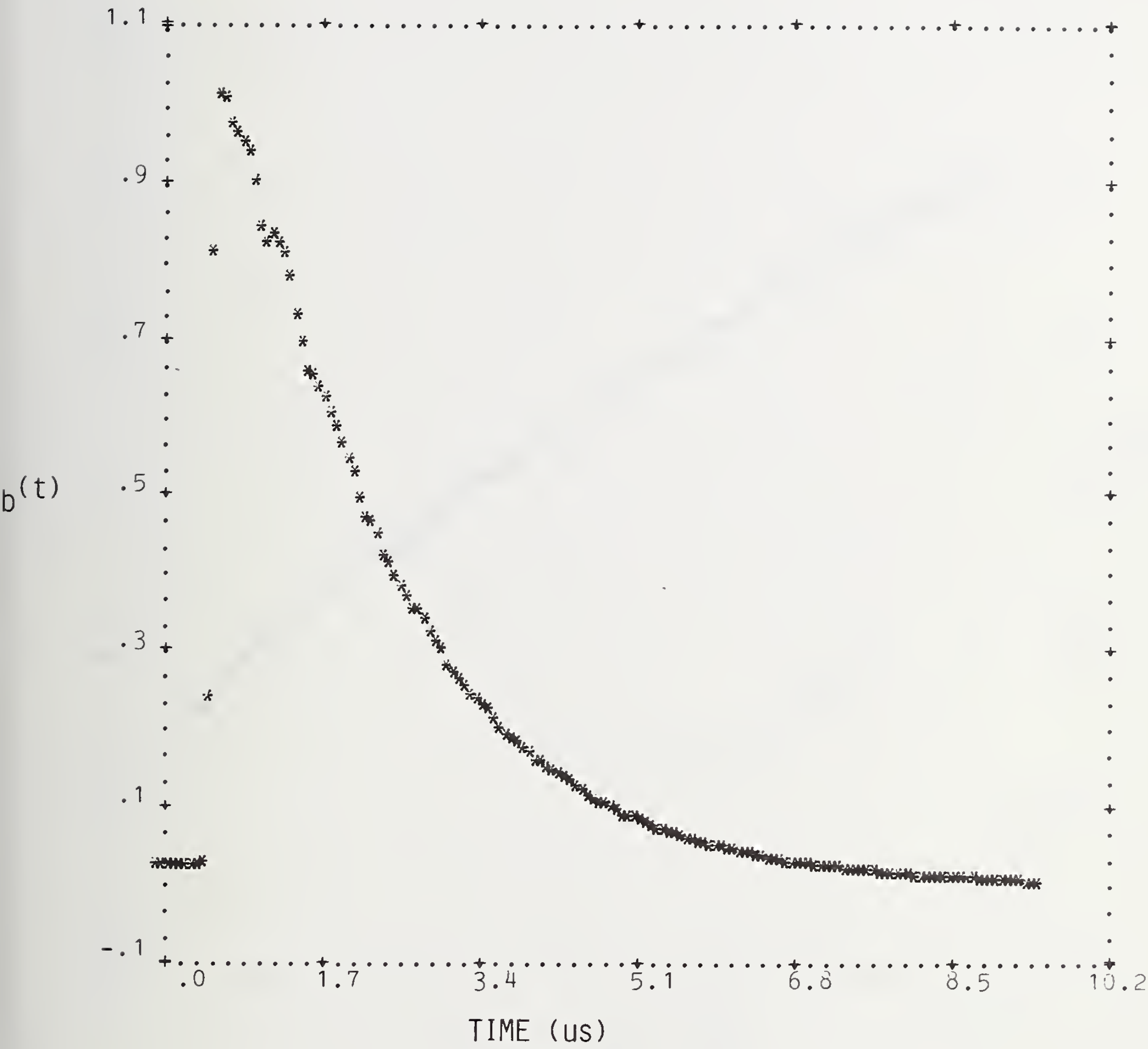


Figure 2. Backscatter signal as a function of time. Graded index fiber, 1300 m.

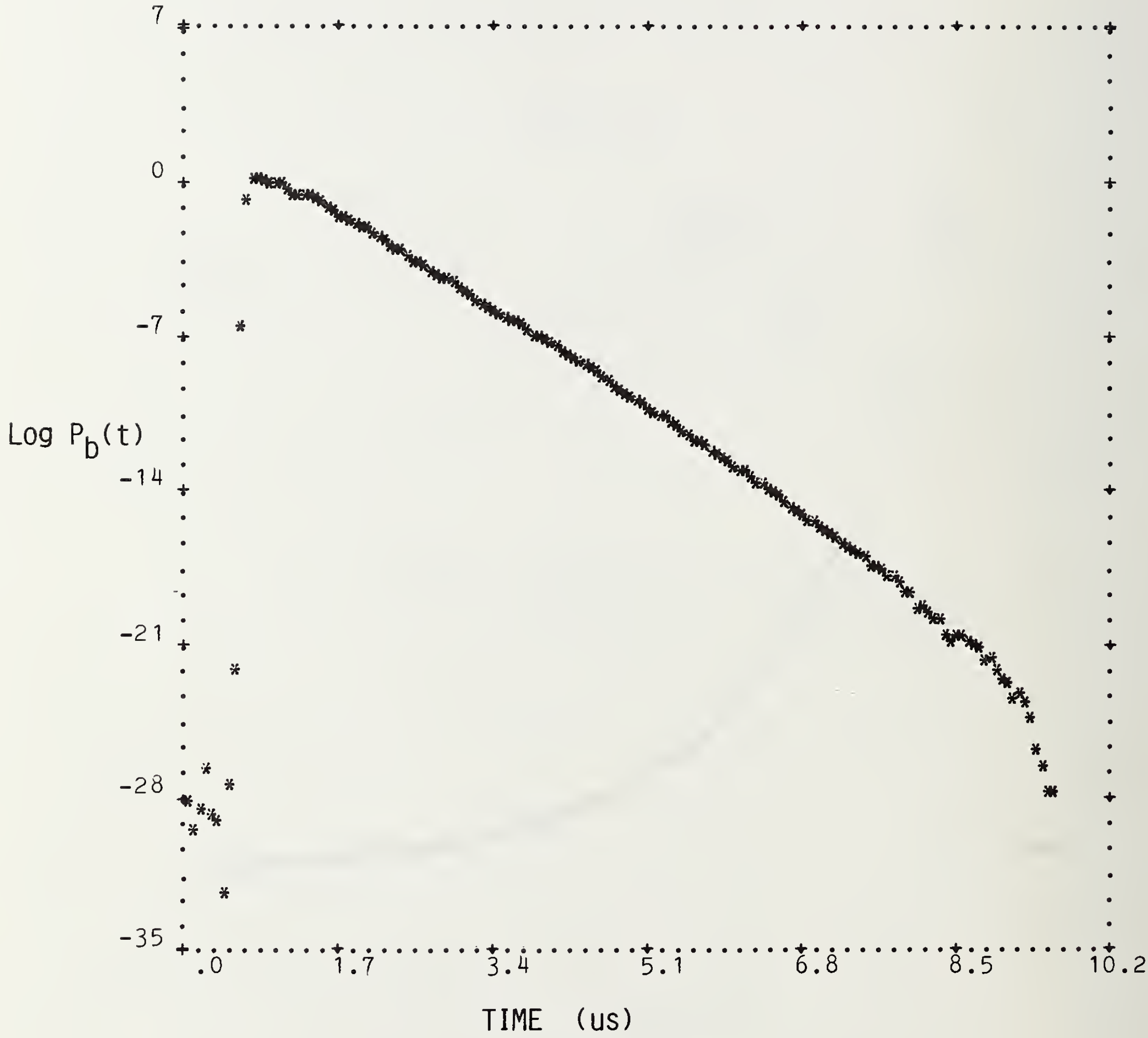


Figure 3. Logarithm of backscatter signal in figure 2.

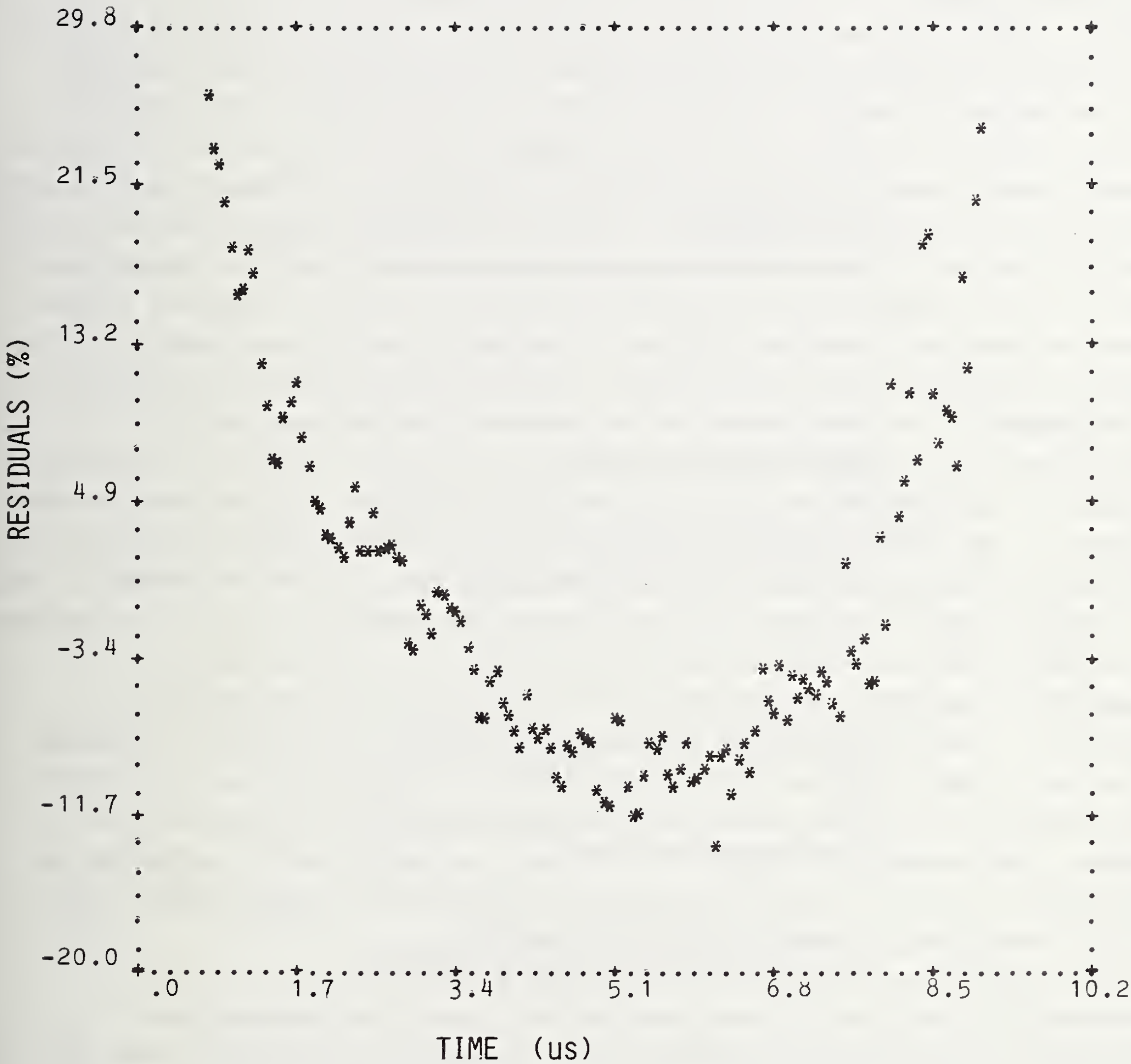


Figure 4. Residuals of least-squares fit to signal in figure 2.

injected into a multimode waveguide of 75 μm core diameter with no non-linear attenuation. However, the thresholds decrease for decreasing fiber core area, so for single-mode operation the possibility of these scattering processes must be considered.

A typical backscatter experimental setup is illustrated schematically in figure 1. Some of the data generated at NBS with this type of apparatus is depicted in figure 2. These data were chosen to illustrate the fact that the backscatter response is not always an exact exponentially decaying function. This work was done with a 10 mW He-Ne laser operating at .6328 μm. The cw laser was pulsed externally by means of an acousto-optic modulator, producing pulses of about 80 ns full width at half maximum. This type of laser was chosen because properties of a TEM_{00} beam allow for careful control of launch conditions and observations and the effect of different mode energy distributions on loss measurements. The polarizing beam splitting cube used in conjunction with the polarized source allows discrimination between one component of the unpolarized Rayleigh backscatter and the polarized Fresnel reflection from the launching optics at the front end of the fiber. This is possible since most fibers will largely depolarize the input pulse within a few centimeters. Further rejection of unwanted reflections can be accomplished with a pinhole spatial filter. As can be seen from the raw data in figure 2, the reflection spike at the input end can be eliminated almost completely. The fiber itself is held in a 6 cm long holder consisting of a precision-bore capillary tube with a microscope cover slide (thickness .1 mm) on the output end. The device is constructed so that the fiber is in contact with an immersion oil which minimizes the effect of fiber surface irregularities as well as performing the function of a mode stripper. Realignment is also facilitated if the fiber needs to be removed. However dust in this type of device can pose problems. The detector used in these experiments was an eleven stage photomultiplier tube with enhanced S-20 response. The boxcar integrator is a signal averaging device producing an analog output which is then digitized and punched out on paper tape. The numerical analysis is done on a digital computer.

The input pulse for the data of figure 2 had a beam waist of approximately 8 μm which is near the optimum value for minimum beam divergence in the graded index fiber [8]. The beam was launched near the center of the 60 μm diameter core. The length of the fiber was 1.38 km with a measured direct attenuation of 13.3 dB/km at .6328 μm.

It is clear from figure 3 that the decay of the backscatter is not perfectly exponential; that is, log $P_b(t)$ is not a straight line. This departure is also graphically demonstrated in the plot of the residuals to the least-squares fit to the backscatter data (figure 4). Several end points have been deleted in this analysis. Other launch conditions can produce a

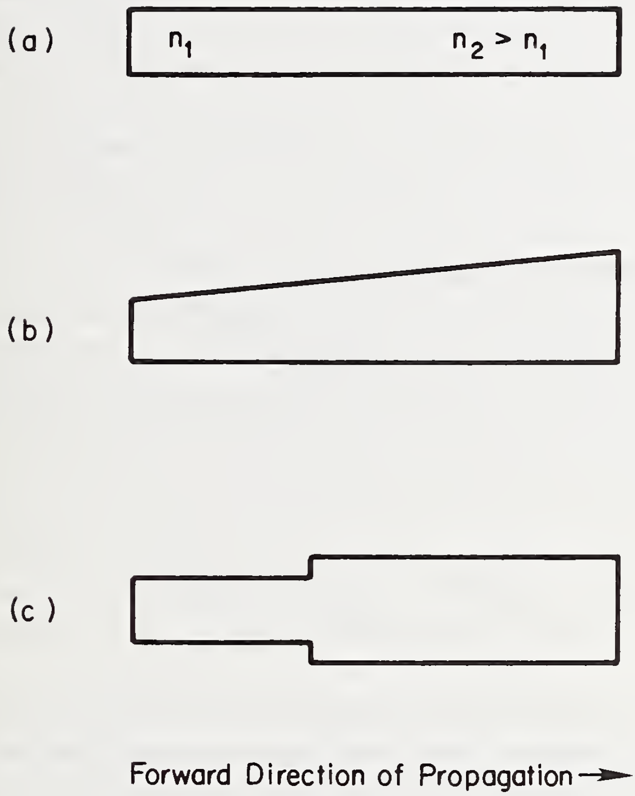


Figure 5. Examples of nonreciprocal waveguide structures.

more nearly linear response. A likely explanation for the observed curvature in this case is that energy is initially coupled into relatively low scattering loss modes and this energy is redistributed into higher scattering loss modes as the pulse propagates down the fiber. This then is an example both of the power of the backscatter technique to probe the details of the loss mechanisms as well as the possibilities for errors in the attenuation determinations outlined in this section.

2. THEORY OF THE OPTICAL TIME DOMAIN REFLECTOMETER

The basic physical process underlying the operation of our time domain reflectometer is Rayleigh scattering which is due to scattering centers that are small compared with a wavelength of light. In optical fibers these centers arise from variations in dopant concentrations or fluctuations in the density (and, consequently, index of refraction) of the glass matrix which occurs when the glass is cooled from the melt. Rayleigh scattering is approximately isotropic and is proportional to the inverse fourth power of the wavelength. This is often the most important source of loss in practical fibers in the wavelength region around .85 μm [9].

Consider a waveguide whose loss and scattering properties are constant along its length to be excited by a pulse whose power is in the form of a delta function $P_f(t) = E_o\delta(t)$ and with unit energy E_o. The pulse propagates down the fiber with group velocity v, so that at a distance x, corresponding to the time $t = x/v$, the energy in the pulse is

$$E_f(x) = E_o \exp\,[-\alpha_1' x], \tag{2-1}$$

where α_1' is the total loss per unit length in the forward direction. In a distance dx the energy removed from the pulse by the Rayleigh scattering loss α_s' is $E_o\alpha_s' dx \exp\,[-\alpha_1' x]$. Of this energy, a fraction C_1 is trapped by the waveguide and is guided in the reverse direction. We will refer to C_1 as the capture fraction. Personick [5] has shown that it is approximately given by

$$C_1 = \frac{(NA)^2}{4N_1^{\,2}} \tag{2-2}$$

for isotropic scattering where NA is the fiber numerical aperture and N_1 is

the index of refraction of the fiber on the core axis. For Rayleigh scattering C_1 must be multiplied by a factor of 3/2 [10].

The energy backscattered from the element dx, and trapped by the waveguide dE_b, then arrives at the input end of the fiber after undergoing an additional attenuation $\exp(-\alpha_2' x]$ due to the total loss per unit length α_2' in the reverse direction. The energy at the input end due to scattering in dx is then

$$dE_b = E_o C_1 \alpha_s' \, dx \exp [-(\alpha_1' + \alpha_2')x] \tag{2-3}$$

Expressed as a function of time at the input $t = 2\, x/v$, the power $P_b(t) = dE_b(t)/dt$ becomes

$$P_b(t) = \frac{E_o C_1 \alpha_s' v}{2} \exp[-2(\alpha_1' + \alpha_2')\frac{vt}{2}] \tag{2-4}$$

We have assumed a fiber with uniform properties. With the further assumption that the total bulk loss in the forward direction is the same as in the reverse direction, $\alpha_1' = \alpha_2'$, then the attenuation of the fiber is easily obtained from the backscatter response of eq (2-4). The attenuation, in decibels, is just $5 \langle\alpha_1'\rangle X_o \log_{10} e$ where $\langle\alpha_1'\rangle$ is the best fit decay constant to the experimental backscatter power data. It is the purpose of this report to examine the magnitude of the derived backscatter attenuation under conditions where the fiber loss exhibits departures from the above assumptions. In order to do this, we will develop a discrete model whose responses can more easily be determined by digital computation methods.

3. ATTENUATION RELATIONS BASED ON A DISCRETE MODEL

In this section we will develop a model for obtaining the backscatter response of an optical fiber which permits comparison of the direct (insertion) loss with the loss estimated by various means from the backscatter signal. We will employ a phenomenological approach using the bulk properties of the fiber. Multiple scattering is neglected. Rather than work with the continuous functions of the previous section, we will find it more convenient in our computer modeling to use a discrete representation for backscatter simulation. Also, our experimental data, discussed in section 7, is analyzed with this type of digital format; the same least-squares program

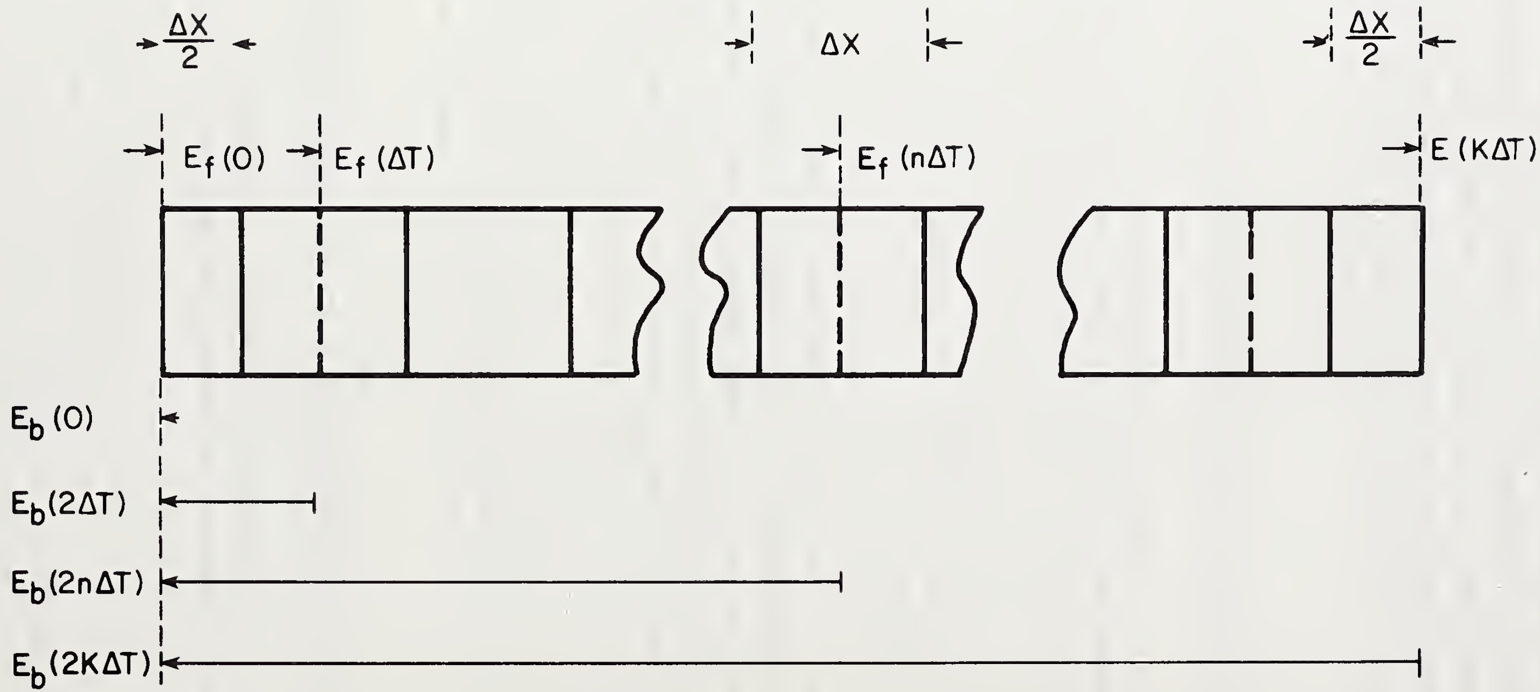


Figure 6. Geometry for discrete waveguide scattering model.

can be used with the computer-generated data.

The fiber loss may be estimated from the backscatter in several ways. The usual approach is to employ a least-squares fit to an expontential decay which we have seen is to be expected from a uniform fiber. This fit may be made to the backscatter signal from the entire fiber, or to successive regions of the fiber which are expected to possess uniform properties. Another approach is to identify the loss with the backscatter power ratio of the first and last measurement points corresponding to the input and output of the fiber. A model which permits the comparison of these backscatter-derived attenuations with the direct attenuation will now be examined. In all respects the model is intended to simulate experimental conditions as discussed in the previous section.

Referring to figure 6, we will find it convenient to sample our fiber of length X_o with k differential elements. A narrow pulse of radiation moves from left to right and the backscatter signal travels in the return direction right to left. The transverse intensity distribution is assumed constant for propagation in both directions. Each of the k elements is considered to be uniform in itself and characterized by bulk parameters as follows:

$A_1(n)$ = absorption loss of the n^{th} element in the forward direction.

$A_2(n)$ = absorption loss of the n^{th} element in the reverse (back) direction.

$S_1(n)$ = scattering loss of the n^{th} element in the forward direction.

$S_2(n)$ = scattering loss of the n^{th} element in the reverse (back) direction.

$C_1(n)$ = capture fraction of the n^{th} element, assumed constant in both directions.

The absorption loss terms, $A_1(n)$ and $A_2(n)$, as used here include all contributions to attenuation which do not return a signal in the direction opposite to the direction of propagation. These include not only intrinsic absorption which converts optical power into heat, but such effects as radiation from bends. Intrinsic absorption has its origins in the extremities of the uv and ir absorption bands as well as components due to impurities and the OH^- and transition metal ions. The scattering loss terms, $S_1(n)$ and $S_2(n)$, are taken to include not only the Rayleigh scattering, but other contributions such as Mie scattering and reflections from cracks and imperfections which return a signal in the direction opposite to the original direction of propagation. For example, a perfect reflection at a fiber break would be represented by $S = (N_1 - 1)^2/(N_1 + 1)^2$ and $C_1 = 1$. Here, N_1 is the index of refraction of the step-index fiber core. Also, we have allowed for the possibility that the fiber is nonreciprocal in the sense that its

properties in the forward propagating direction may not be identical to the corresponding properties in the reverse direction. Such a situation can arise since it is well known that intrinsic loss and scattering loss are mode dependent quantities [2,9]. For example, launching conditions can be such that relatively low loss modes are excited in the forward direction. However, Rayleigh scattering, being approximately isotropic, can excite a different set of modes whose average loss is somewhat higher. Some additional examples of nonreciprocal behavior are illustrated in figure 2. Effects of this sort have also been observed experimentally [11]. Nonreciprocity, as we shall see, can result in significant discrepancies in backscatter estimates of loss in multimode fibers.

In the following discussion we will label the quantities traveling in the forward direction with the subscript f and the corresponding quantities traveling in the backward direction with the subscript b. We then have

$E_b(2n\Delta T)$ = Energy of the back traveling pulse scattered from n^{th} differential element measured at input end of fiber at time $2n\Delta T$.

$E_f(n\Delta T)$ = Energy of the forward traveling input pulse measured at the center of the n^{th} differential element at time $n\Delta T$.

$P_b(2n\Delta T)$ = Average power in time interval $2\Delta T$ in backscatter signal at time $2n\Delta T$.

$P_f(n\Delta T)$ = Average input power in n^{th} differential element,

where ΔT is the one way transit time of a narrow pulse across an element. For reasons of convenience, all the elements in figure 6 of length $\Delta x = v\Delta T$ except for the first ($n=0$) and last ($n=k$) which are of length $v\Delta T/2$. Here v is the pulse group velocity. This choice is arbitrary, but it allows for the backscatter energy $E_b(2n\Delta T)$ and forward propagating pulse energy $E_f(n\Delta T)$ to be sampled at the same physical point.

For simplicity, the waveguide is excited with a pulse whose power is in the form of a delta function with unit energy

$$P_f(0) = E_f\delta(t), \qquad (3\text{-}1)$$

$$E_f(0) = 1. \qquad (3\text{-}2)$$

The extension to pulses of arbitrary length is considered in section 6.

3.1 Direct Attenuation

We may now calculate the energy in the interrogating pulse as a function of time as it propagates through each of the n discrete elements of the waveguide. If the absorption loss and scattering loss parameters $A_1(n)$, $A_2(n)$, $S_1(n)$, and $S_2(n)$ are small, the progressive energy of the pulse is given approximately by the relations

$$E_f(0) = 1, \tag{3-3}$$

$$E_f(\Delta T) = E_f(0) \left[1 - \frac{A_1(1)}{2}\right] \left[1 - \frac{A_1(0)}{2}\right] \left[1 - \frac{S_1(1)}{2}\right] \left[1 - \frac{S_1(0)}{2}\right], \tag{3-4}$$

with the recurrence relation

$$E_f(n\Delta T) = E_f\left((n-1)\Delta T\right) \left[1 - \frac{A_1(n)}{2}\right] \left[1 - \frac{A_1(n-1)}{2}\right]$$

$$\left[1 - \frac{S_1(n)}{2}\right] \left[1 - \frac{S_1(n-1)}{2}\right], \tag{3-5}$$

and for k elements

$$\frac{E_f(k\Delta t)}{E_f(0)} = \prod_{n=1}^{k} \left[1 - \frac{A_1(n)}{2}\right]^2 \left[1 - \frac{S_1(n)}{2}\right]^2$$

$$\left[1 - \frac{A_1(0)}{2}\right] \left[1 - \frac{S_1(0)}{2}\right] \left[1 - \frac{A_1(k)}{2}\right] \left[1 - \frac{S_1(k)}{2}\right]. \tag{3-6}$$

The direct attenuation L_1, in decibels, for the present pulsed system is most conveniently represented in terms of pulse energy, rather than power, and for our purposes is defined as

$$L_1 = -10 \log \left[\frac{E_f(k\Delta T)}{E_f(0)}\right] \text{ dB} \tag{3-7}$$

or finally

$$-\frac{L_1}{10} = 2 \sum_{n=1}^{k-1} \left(\log\left[1-\frac{A_1(n)}{2}\right] + \log\left[1-\frac{S_1(n)}{2}\right]\right)$$

$$+ \log\left[1-\frac{A_1(k)}{2}\right] + \log\left[1-\frac{S_1(k)}{2}\right]$$

$$+ \log\left[1-\frac{A_1(0)}{2}\right] + \log\left[1-\frac{S_1(0)}{2}\right] \qquad (3\text{-}8)$$

3.2 Two-Point Backscatter Attenuation

We now examine the relations for the energy in the backscattered pulse as a function of time. Each contribution to the backscatter signal $E_b(2n\Delta T)$ originates at the center of the respective scattering element. With the same small loss approximations as before

$$E_b(0) = \frac{E_f(0)\ S_1(0)\ C_1(0)}{2} \qquad (3\text{-}9)$$

$$E_b(2\Delta T) = E_f(\Delta T)\ S_1(1)\ C_1(1)\ \left[1-\frac{A_2(1)}{2}\right]\left[1-\frac{A_2(0)}{2}\right]$$

$$\left[1-\frac{S_1(1)}{2}\right]\left[1-\frac{S_2(0)}{2}\right] \qquad (3\text{-}10)$$

$$E_b(4\Delta T) = E_f(2\Delta T)\ S_1(2)\ C_1(2)\ \left[1-\frac{A_2(2)}{2}\right]\left[1-\frac{A_2(1)}{2}\right]^2$$

$$\left[1-\frac{A_2(0)}{2}\right]\left[1-\frac{S_2(2)}{2}\right]\left[1-\frac{S_2(1)}{2}\right]^2\left[1-\frac{S_2(0)}{2}\right] \qquad (3\text{-}11)$$

and

$$E_b(2n\Delta T) = E_f(n\Delta T)\ S_1(n)\ C_1(n) \prod_{J=1}^{n-1} \left[1-\frac{A_2(j)}{2}\right]^2$$

$$\left[1-\frac{S_2(j)}{2}\right]^2 \left[1-\frac{A_2(n)}{2}\right]\left[1-\frac{A_2(0)}{2}\right]$$

$$\left[1-\frac{S_2(n)}{2}\right]\left[1-\frac{S_2(0)}{2}\right] \qquad (3\text{-}12)$$

From eq (3-12) we may derive the following approximate recurrence relation:

$$\frac{E_b(2n\Delta t)}{E_b(2(n-1)\Delta T)} = \frac{S_1(n)\ C_1(n)}{S_1(n-1)\ C_1(n-1)} \left[1-\frac{A_1(n)}{2}\right] \left[1-\frac{A_1(n-1)}{2}\right]$$

$$\left[1-\frac{A_2(n)}{2}\right] \left[1-\frac{A_2(n-1)}{2}\right] \left[1-\frac{S_1(n)}{2}\right] \left[1-\frac{S_1(n-1)}{2}\right]$$

$$\left[1-\frac{S_2(n)}{2}\right] \left[1-\frac{S_2(n-1)}{2}\right] \tag{3-13}$$

and for the final k^{th} element

$$\frac{E_b(2k\Delta T)}{E_b(2(k-1)\Delta T)} = \frac{S_1(k)\ C_1(k)}{2\ S_1(k-1)C_1(k-1)} \left[1-\frac{A_1(k)}{2}\right]$$

$$\left[1-\frac{A_1(k-1)}{2}\right] \left[1-\frac{A_2(k)}{2}\right] \left[1-\frac{A_2(k-1)}{2}\right] \left[1-\frac{S_1(k)}{2}\right]$$

$$\left[1-\frac{S_1(k-1)}{2}\right] \left[1-\frac{S_2(k)}{2}\right] \left[1-\frac{S_2(k-1)}{2}\right] \tag{3-14}$$

Successive applications of the above equations give

$$\frac{E_b(2k\Delta T)}{E_b(0)} = \frac{S_1(k)\ C_1(k)}{S_1(0)\ C_1(0)} \prod_{n=1}^{k\ 1} \left[1-\frac{A_1(n)}{2}\right]^2 \left[1-\frac{A_2(n)}{2}\right]^2$$

$$\left[1-\frac{S_1(n)}{2}\right]^2 \left[1-\frac{S_2(n)}{2}\right]^2 \left[1-\frac{A_1(k)}{2}\right] \left[1-\frac{A_2(k)}{2}\right]$$

$$\left[1-\frac{S_1(k)}{2}\right] \left[1-\frac{S_2(k)}{2}\right] \left[1-\frac{A_1(0)}{2}\right] \left[1-\frac{A_2(0)}{2}\right]$$

$$\left[1-\frac{S_1(0)}{2}\right] \left[1-\frac{S_2(0)}{2}\right] \tag{3-15}$$

The two-point backscatter attenuation L_3, in decibels, can now be defined for k elements as

$$L_3 = \frac{-10}{2} \log \left[\frac{E_b(2k\Delta T)}{E_b(0)}\right]. \tag{3-16}$$

With the aid of eq (3-15) this may be written as

$$\begin{aligned}
\frac{-L_3}{5} = \log & \left[\frac{S_1(k)\ C_1(k)}{S_1(0)\ C_1(0)}\right] \\
& + \log \left[1- \frac{A_2(k)}{2}\right] + \log \left[1- \frac{A_2(0)}{2}\right] \\
& + \log \left[1- \frac{S_2(k)}{2}\right] + \log \left[1- \frac{S_2(0)}{2}\right] \\
& + \log \left[1- \frac{A_1(k)}{2}\right] + \log \left[1- \frac{A_1(0)}{2}\right] \\
& + \log \left[1- \frac{S_1(k)}{2}\right] + \log \left[1- \frac{S_1(0)}{2}\right] \\
& + 2 \sum_{n=1}^{k=1} \left(\log \left[1- \frac{A_2(n)}{2}\right] + \log \left[1- \frac{S_2(n)}{2}\right]\right. \\
& + 2 \sum_{n=1}^{k=1} \left(\log \left[1- \frac{A_1(n)}{2}\right] + \log \left[1- \frac{S_1(n)}{2}\right]\right.
\end{aligned} \tag{3-17}$$

If the optical waveguide has reciprocal bulk properties, that is

$$A_1(n) = A_2(n) \tag{3-18}$$

and

$$S_1(n) = S_2(n) \tag{3-19}$$

for all n, then from eq (3-8), we may put eq (3-17) in the form

$$L_3 = L_1 + \tfrac{1}{2} \log \left[\frac{S(k)\ C_1(k)}{S(0)\ C_1(0)}\right]. \tag{3-20}$$

We have dropped the subscripts on S since there is now no directional dependence of the scattering. Under the additional condition that the product of the scattering loss and capture fraction is the same at the first and last observation points, or

$$S(k)\ C_1(k) = S(0)\ C_1(0), \tag{3-21}$$

the two point backscatter attenuation agrees with the insertion method; $L_3 = L_1$. Some computer generated examples which illustrate this important result are presented in section 4.

In cases where eq (3-21) is not valid (but the waveguide is reciprocal), for example where two dissimilar fibers are joined, an exact identification between L_1 and L_3 can still be made. This is done by interchanging the input and output ends of the fiber and repeating the backscatter measurements. This can be shown as follows: We denote by a prime the second set of measurements where input and output ends are interchanged from the first set of measurements (unprimed) given in eq (3-20).

$$L_3 = L_1 + \tfrac{1}{2} \log \left[\frac{S(k)\ C_1(k)}{S(0)\ C_1(0)}\right] \tag{3-22}$$

$$L_3' = L_1' + \tfrac{1}{2} \log \left[\frac{S'(k)\ C_1'(k)}{S'(0)\ C_1'(0)}\right] \tag{3-23}$$

but

$$L_1' = L_1 \tag{3-24}$$

and, by definition,

$$S'(k) = S(0) \tag{3-25}$$

$$S'(0) = S(k) \tag{3-26}$$

$$C_1'(k) = C_1(0) \tag{3-27}$$

By taking the mean of eqs (3-22) and (3-23) we have

$$L_1 = \tfrac{1}{2}(L_3 + L_3') \tag{3-28}$$

The arithmetic mean of the two backscatter measurements is equal to the attenuation. This relation is expressed in decibels. The corresponding equation in terms of the signals $E_b(t)$ is

$$L_1 - \frac{-10}{2} \log \left[\frac{E_b(2k\Delta t)\ E_b'(2k\Delta T)}{E_b(o)\ E_b'(0)}\right] \tag{3-29}$$

In all the foregoing discussion we have used energy variables rather than power variables in order to avoid computational complexities resulting from the singular nature of our assumed interrogating pulse $P_f(t) = E_f\delta(t)$. Henceforth we will approximate the backscatter power due to the n^{th} element, and observed at time $2n\Delta T$, as $P_b(2n\Delta T) = E_b(2n\Delta T)/2\Delta T$, and will delete the explicit labeling $2\Delta T$. With this understanding we write $P_b(n) = E_b(n)$.

3.3 Least-Squares Backscatter Attenuation

We have seen in section 2 that the expected temporal dependence of the backscatter signal for a uniform fiber is an exponential decrease with decay constant 2 αv. It is reasonable, therefore, to estimate the attenuation from experimental data by classical discrete curve-fitting techniques. The usual approach [12], is to use a least-squares fit. The techniques of least-squares curve-fitting are discussed in standard references [13] and only some of the basic concepts will be mentioned here. The least-squares program minimizes the sum of squares of deviations of the backscatter variable. The correlation coefficient r is a measure of the goodness of fit of the given data to the assumed exponential dependence. The correlation coefficient varies between 1.0, for a perfect association between calculated and experimental values, and 0.0 for a complete random relation. The

magnitude of r has rather little significance here except to demonstrate the fact that low values of the correlation coefficient imply that other methods (in particular, piecewise fitting) may be more appropriate. The residuals may also be used in this connection as a diagnostic. Residuals represent the difference between the calculated least-squares value of the scattering variable and the experimental value. Examination of the residuals often provide information on the type and location of imperfections.

In using the least-squares approach in the present discrete context, it is necessary to disregard the first and last points in order to obtain exact agreement with the direct attenuation. This is a result of the details of our scattering model which assigns a backscatter power value midway between adjacent values at points where discontinuities occur. The relation between the best fit of the exponential decay constant to the backscatter signal in our discrete model is obtained from eq (3-15). Assume all elements have identical, but not necessarily reciprocal, loss values: $A_1(n) = A_1$, $A_2(n) = A_2$, $S_1(n) = S_1$, $S_2(n) = S_2$, $C_1(n) = C_1$ for all n. Then eq (3-15) becomes, for a constant (unity) fiber length and increasing number of elements, k,

$$\lim_{k\to\infty} \frac{P_b(k)}{P_b(0)} = \lim_{k\to\infty} [1-\frac{A_1}{2}]^{2k} [1-\frac{A_2}{2}]^{2k} [1-\frac{S_1}{2}] [1-\frac{S_2}{2}]^{2k} , \quad (3\text{-}30)$$

but the loss values per element are defined to be

$$A_1 + S_1 = \alpha_1/k \quad (3\text{-}31)$$

and

$$A_2 + S_2 = \alpha_2/k \quad (3\text{-}32)$$

Equation (3-30) then becomes

$$P_b(k) = P_b(0) \exp [-(\alpha_1 + \alpha_2] \quad (3\text{-}33)$$

by definition of the exponential function. The least-squares method yields the best fit $\langle\alpha\rangle_b$ to this exponential. For the reciprocal case usually considered $\alpha_1 = \alpha_2$, so that

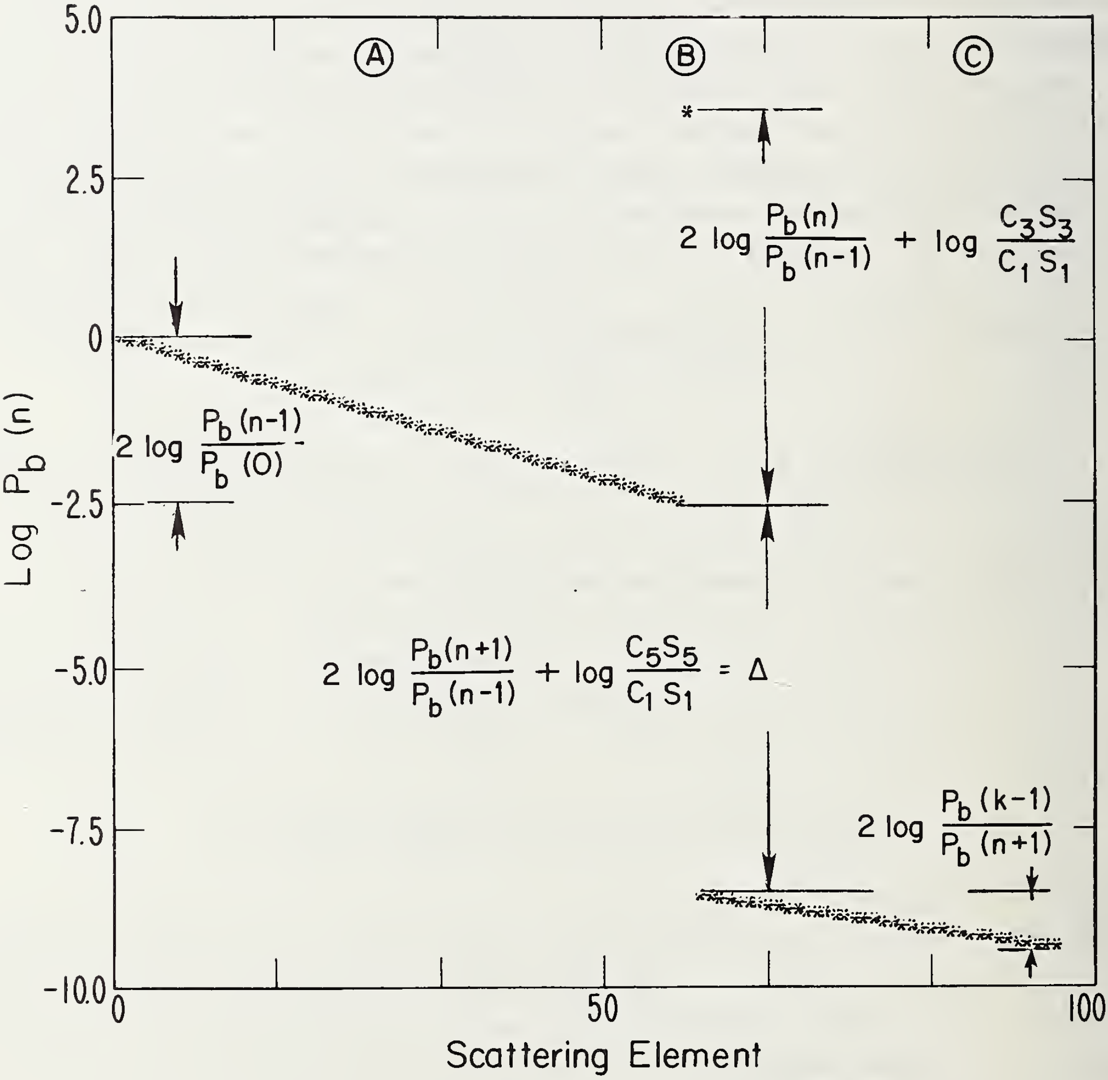


Figure 7. Logarithm of backscatter power as a function of scattering element for a fiber with three distinct loss regions.

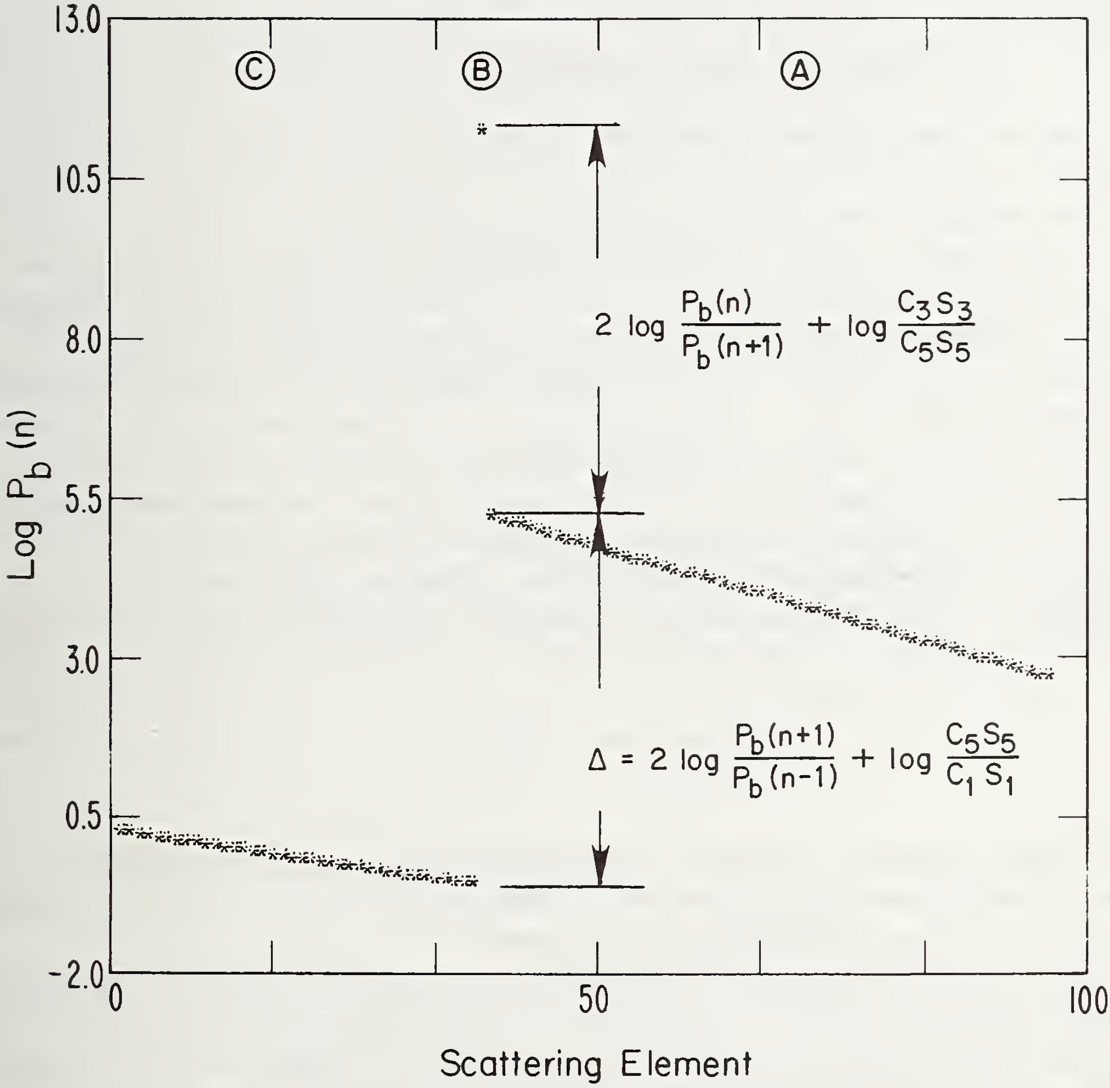


Figure 8. Complementary loss signature for fiber in figure 7. This corresponds to reversing the fiber end for end.

$$\langle\alpha\rangle_b = 2(\alpha_1). \tag{3-34}$$

The least-squares method used with our model is therefore expected to agree with the theory given in section 2 for sufficiently large number of points and uniform reciprocal fiber. Departure from uniformity produces an effect on attenuation values that is most conveniently demonstrated by our computer-generated examples given in section 4.

3.4 Piecewise Least-Squares Backscatter Attenuation

When the least-squares technique is employed for estimating loss in fibers which consist of more than one uniform region connected sequentially along the length of the guide, accuracy is improved if the curve fitting is done in a piecewise manner. This is illustrated in figure 7. Here is an example of two dissimilar regions, A and C, joined at an interface, region B, which has scattering and capture properties different from the bulk properties at either end. The loss values chosen for this example are given in run 650 (section 4.2). Curve fitting to the overall guide in this case will generally give rather poor agreement with the insertion loss value. However, taking a least-squares fit to regions A and C successively giving, $L_2(A)$ and $L_2(C)$, and estimating the total attenuation in region B, Δ, as indicated by the arrows in figure 7, gives a more accurate value of attenuation. In this approximation, the total piecewise attenuation L_4 is

$$L_4 = L_2(A) + L_2(C) + \Delta. \tag{3-35}$$

We will show, however, that these approximations may contain significant errors in cases where the scattering parameters and capture fractions are not identical in the two uniform regions (A and C).

When using this approach to determine the insertion loss of couplers or splices, it should be kept in mind that at such points the pulse can be relaunched with a different mode distribution of energies. Non-equilibrium conditions can introduce significant complexities in the interpretation of the backscatter signals.

3.5 Algorithm for Backscatter Comparisons

The discrete representation for fiber attenuation developed in the previous sectons is suited for calculations on a digital computer. A program

was developed which allows the transmitted power $P_f(n)$ and backscatter power $P_b(2n)$ to be calculated for each successive element n in the fiber of figure 6 when selected values are chosen for $A_1(n)$, $A_2(n)$, $S_1(n)$, $S_2(n)$, and $C_1(n)$. This was intended to simulate various types of imperfections, defects, fractures, and general departures from a uniform fiber. Under these conditions the different values for total attenuation, denoted by L_1, L_2, L_3, and L_4 can be compared. This is done by evaluating eqs (3-8), (3-17), (3-35), as well as the least squares value. We have assumed that the direct attenuation, L_1, yields the "correct" value since it can be measured directly (under specified launch conditions and for a given length). The differences L_1-L_2, L_1-L_3, and L_1-L_4 are then considered to be "errors" in estimating this attenuation.

4. COMPUTED EXAMPLES

This section contains examples of several types of loss pathologies and the effect they have on backscatter attenuation estimates.

4.1 Point Defects

Examples in this section simulate the condition in which defects occur in a region of the fiber ΔX which is smaller than or comparable to $v\Delta T$ where ΔT is the assumed input pulse duration. The fiber is otherwise uniform. This type of perturbation could include such inhomogeneity sources as bubbles, isolated contamination regions, particulates, and cracks.

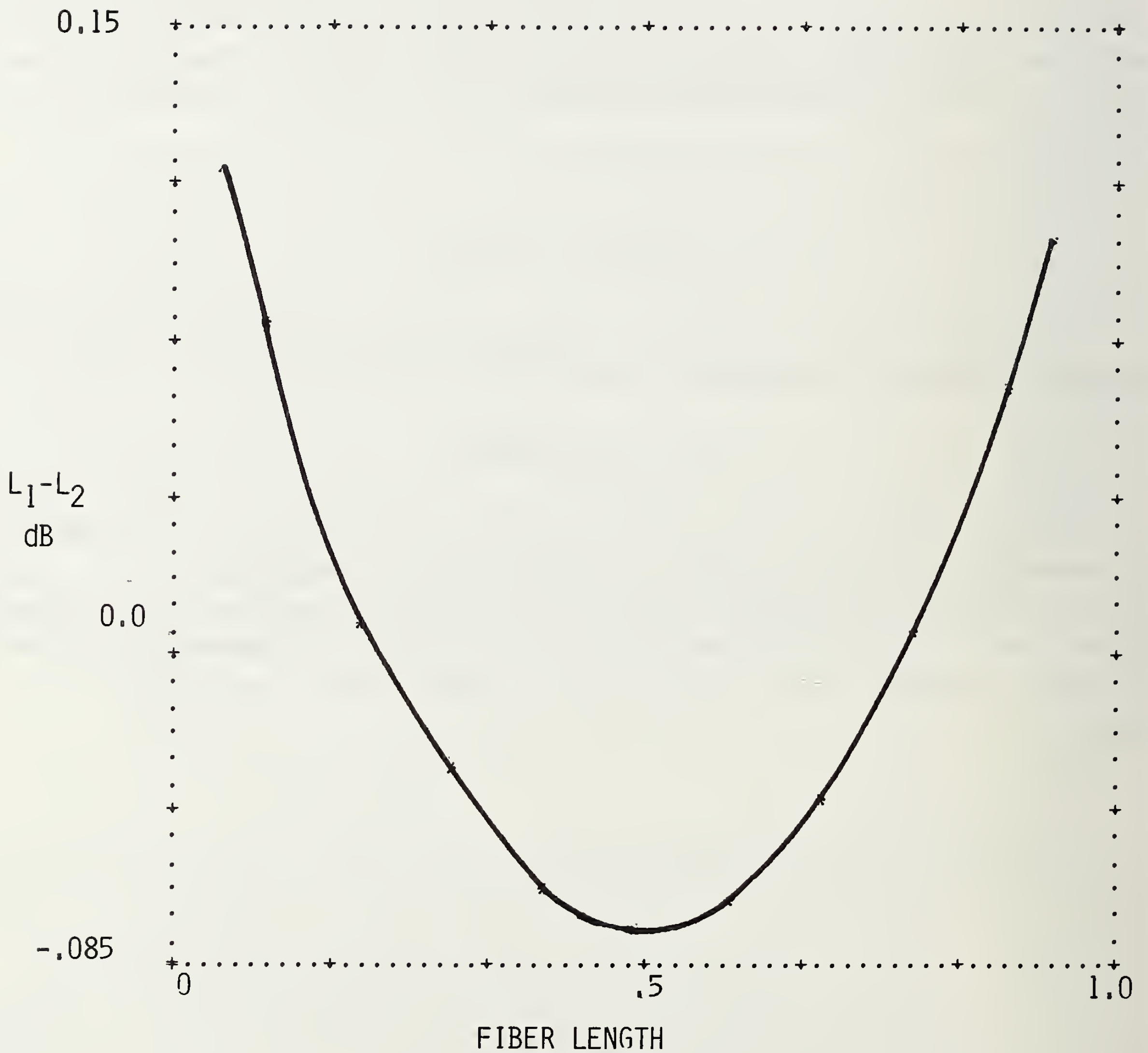
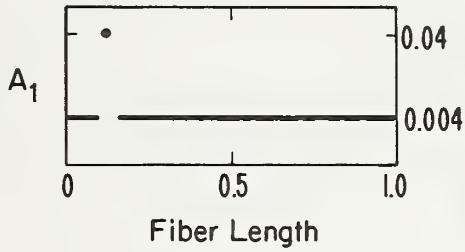


Figure 9. Least-squares error for a point absorption-loss imperfection as a function of its location along the fiber. Details are given in run 500.

RUN : 500

VARIABLE: A_1



$A_1 = 0.004 \quad n \neq 4$

$A_1 = 0.040 \quad n = 4$

$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004 to 0.040
A_2	Back absorption loss	=	0.004 to 0.040
A_3	Total forward loss	=	0.005 to 0.041
A_4	Total back loss	=	0.005 to 0.041
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

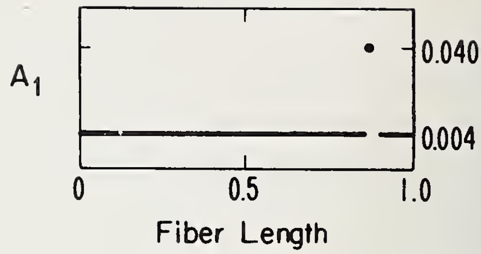
L_1	Direct attn.	=	2.309676 dB
L_2	Least-sq. attn.	=	2.191924 dB
r	Corr. coeff. for L_2	=	0.9978675
L_1-L_2		=	0.117752 dB
L_4	Piecewise attn.	=	2.309676 dB
L_1-L_4		=	0.0 dB
L_3	Two-point attn.	=	2.309676 dB
L_1-L_3		=	0.0 dB

REMARKS:

Run 500 simulates a fiber with a point defect possessing excess absorption loss, the other parameters remaining unaffected. The values of the least-squares attenuation L_2 will depend on the location of the defect, as shown in runs 501, 503 and figure 9. If the loss is sufficiently large that its presence is indicated on the backscatter signature, then improved accuracy may be obtained from a piecewise least-squares fit. The two-point method yields the correct attenuation.

RUN: 503

VARIABLE: A_1



$A_1 = 0.004 \quad n \neq 95$

$A_1 = 0.040 \quad n = 95$

$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004 to 0.040
A_2	Back absorption loss	=	0.004 to 0.040
A_3	Total forward loss	=	0.005 to 0.041
A_4	Total back loss	=	0.005 to 0.041
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.309677 dB
L_2	Least-sq. attn.	=	2.191924 dB
r	Corr. coeff. for L_2	=	0.9978674
$L_1 - L_2$		=	0.117753 dB
L_4	Piecewise attn.	=	2.309676 dB
$L_1 - L_4$		=	0.000001 dB
L_3	Two-point attn.	=	2.309676 dB
$L_1 - L_3$		=	0.000001 dB

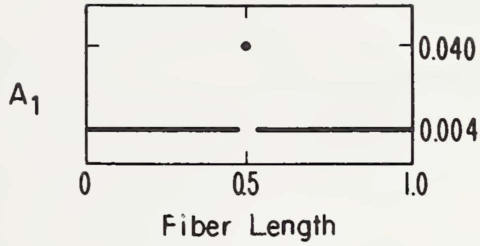
REMARKS:

See run 500.

This example illustrates for effect of reversing run 500 end for end. The value of L_2 in the two directions is the same.

RUN: 501

VARIABLE: A_1



$A_1 = 0.004 \; n \neq 50$

$A_1 = 0.040 \; n = 50$

$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004 to 0.040
A_2	Back absorption loss	=	0.004 to 0.040
A_3	Total forward loss	=	0.005 to 0.041
A_4	Total back loss	=	0.005 to 0.041
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.309677 dB
L_2	Least sq. attn.	=	2.386327 dB
r	Corr. coeff. for L_2	=	0.9969112
L_1-L_2		=	-0.076650 dB
L_4	Piecewise attn.	=	2.309677 dB
L_1-L_4		=	0.0
L_3	Two-point attn.	=	2.309676 dB
L_1-L_3		=	0.000001 dB

REMARKS:

See run 500

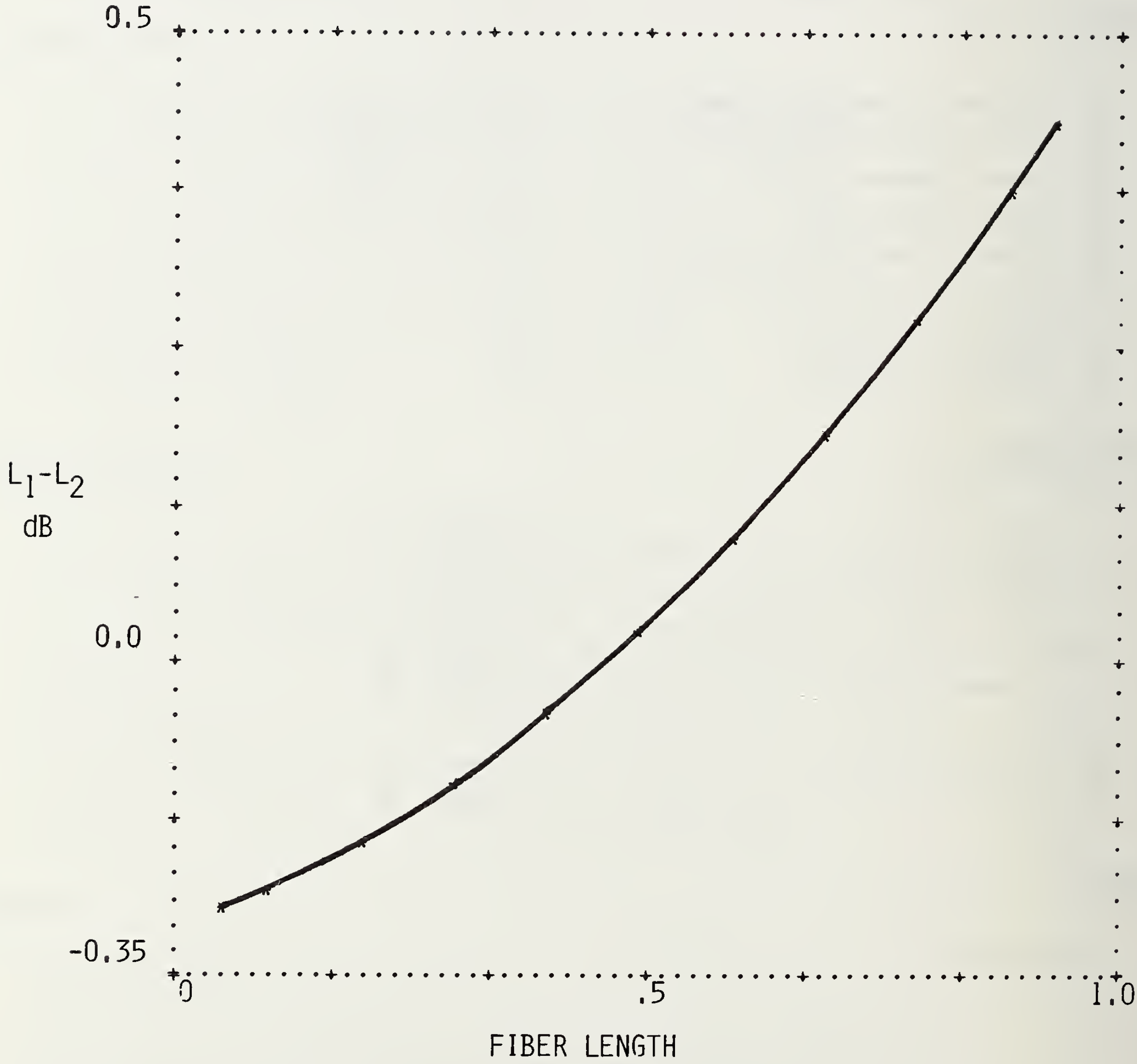
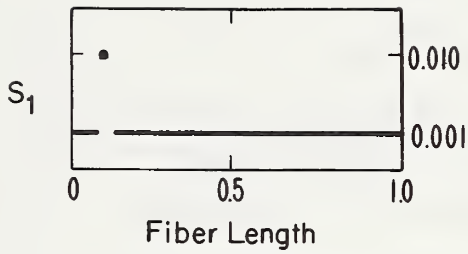


Figure 10. Least-squares error for a point scattering-loss imperfection as a function of its location along the fiber. Details are given in run 507.

RUN: 507

VARIABLE: S_1

$S_1 = 0.001$ $n \neq 4$
$S_1 = 0.010$ $n = 4$
$S_1 = S_2$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005 to 0.014
A_4	Total back loss	=	0.005 to 0.014
S_1	Forward scattering loss	=	0.001 to 0.010
S_2	Back scattering loss	=	0.001 to 0.014
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.190782 dB
L_2	Least-sq. attn.	=	2.431885 dB
r	Corr. coeff. for L_2	=	0.6744755
L_1-L_2		=	-0.241103 dB
L_4	Piecewise attn.	=	2.190781 dB
L_1-L_4		=	0.000001 dB
L_3	Two-point attn.	=	2.190781 dB
L_1-L_3		=	-0.000001 dB

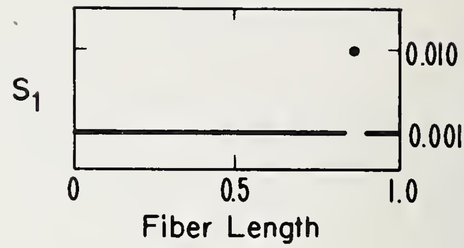
REMARKS:

Run 507 is analagous to run 500 with the exception that the point defect involves excess scattering loss, other parameters being held constant. The effect on L_2 differs in sign and magnitude from the previous example. Runs 506, 505 and figure 10 show the variation of L_2 as a function of defect location. As before, if the perturbation is sufficiently large that it can be detected in the backscatter signature, the piecewise least-squares fit may be employed. The two-point method yields the correct attenuation.

RUN: 505

VARIABLE: S_1

$S_1 = 0.001 \quad n \neq 95$
$S_1 = 0.010 \quad n = 95$
$S_2 = S_1$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005 to 0.014
A_4	Total back loss	=	0.004 to 0.014
S_1	Forward scattering loss	=	0.001 to 0.010
S_2	Back scattering loss	=	0.001 to 0.010
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.190782 dB
L_2	Least-sq. attn.	=	1.891291 dB
r	Corr. coeff. for L_2	=	0.5588888
L_1-L_2		=	0.2994910 dB
L_4	Piecewise attn.	=	2.190782 dB
L_1-L_4		=	0.0
L_3	Two-point attn.	=	2.190781 dB
L_1-L_3		=	0.000001 dB

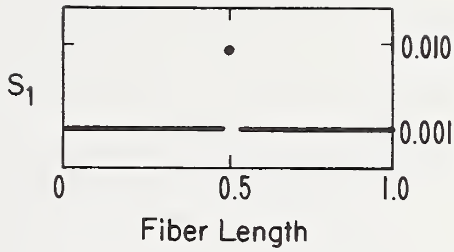
REMARKS:

See run 507.

This run corresponds to reversing the fiber end for end over run 507. The average value for L_2 in the two directions is 2.161588 dB, which is a much improved value over the one-way results, but is still not exactly equal to L_1. As in other cases involving point defects, L_3 and L_4 give correct results. We will see in other examples that increased scatter near the output end of the fiber will yield too low a value for L_2.

RUN: 506

VARIABLE: S_1



$S_1 = 0.001 \quad n \neq 50$

$S_1 = 0.01 \quad n = 50$

$S_2 = S_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005 to 0.014
A_4	Total back loss	=	0.005 to 0.014
S_1	Forward scattering loss	=	0.001 to 0.01
S_2	Back scattering loss	=	0.001 to 0.01
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.190782 dB
L_2	Least-sq. attn.	=	2.212755 dB
r	Corr. coeff. for L_2	=	0.6270513
L_1-L_2		=	-0.021973 dB
L_4	Piecewise attn.	=	2.190781 dB
L_1-L_4		=	0.000001 dB
L_3	Two-point attn.	=	2.190781 dB
L_1-L_3		=	0.000001 dB

REMARKS:

See run 507.

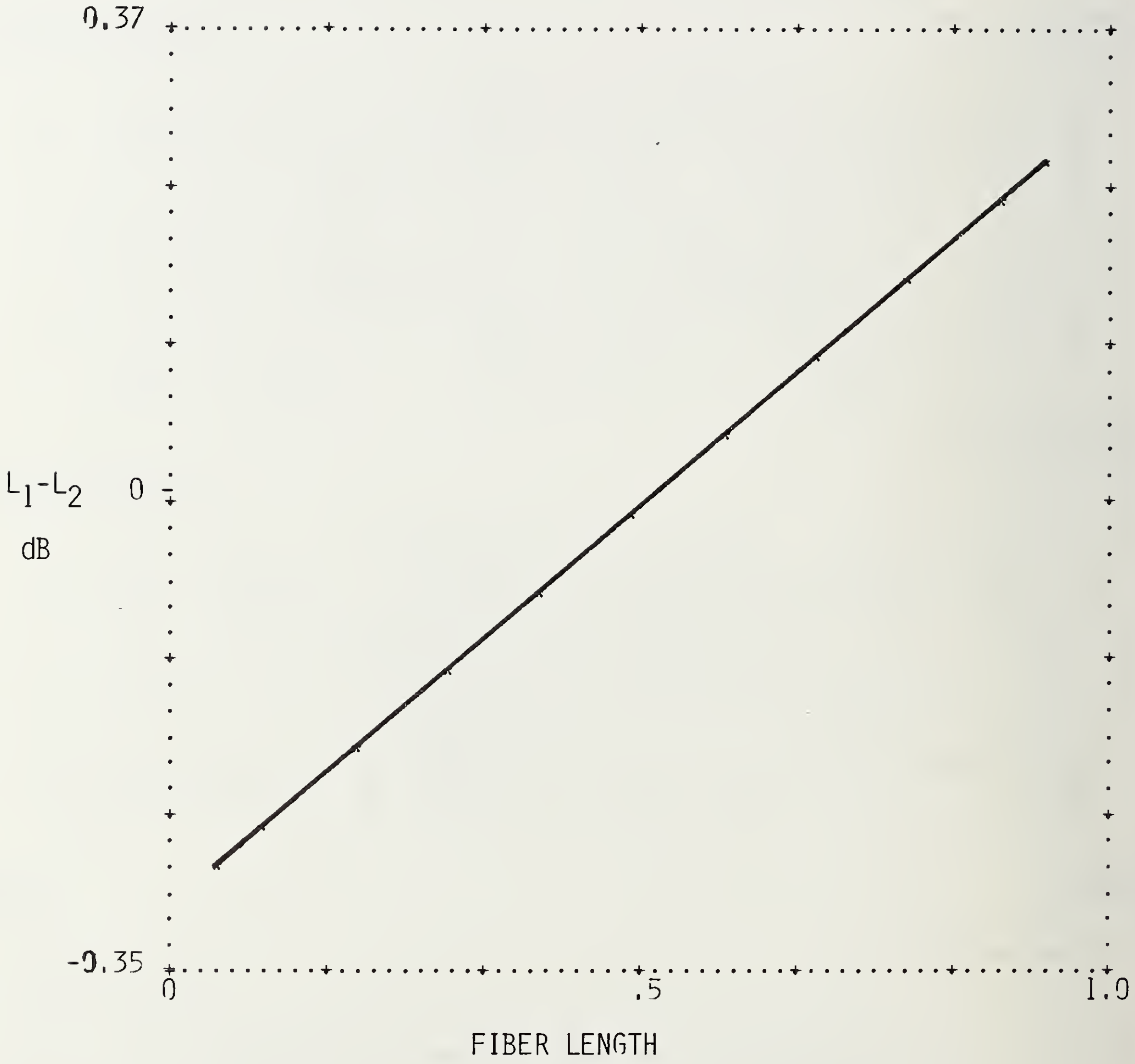
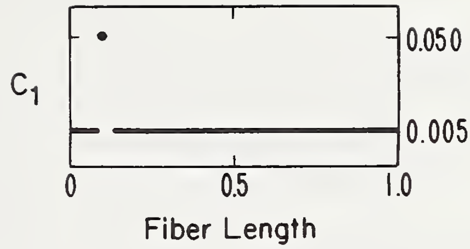


Figure 11. Least-squares error for a point capture fraction imperfection as a function of its location along the fiber. Details are given in run 660.

RUN: 660

VARIABLE: C_1



$C_1 = 0.005 \quad n \neq 4$

$C_1 = 0.050 \quad n = 4$

PARAMETER VALUES:

A_1	Forward absorption loss	= 0.004
A_2	Back absorption loss	= 0.004
A_3	Total forward loss	= 0.005
A_4	Total back loss	= 0.005
S_1	Forward scattering loss	= 0.001
S_2	Back scattering loss	= 0.001
C_1	Capture fraction	= 0.005 to 0.050
K	Number of points	= 100

COMPUTED RESULTS:

L_1	Direct attn.	= 2.151587 dB
L_2	Least-sq. attn.	= 2.421884 dB
r	Corr. coeff. for L_2	= 0.6739156
L_1-L_2		= -0.270297 dB
L_4	Piecewise attn.	= 2.151587 dB
L_1-L_4		= 0.0 dB
L_3	Two-point attn.	= 2.151587 dB
L_1-L_3		= 0.0 dB

REMARKS:

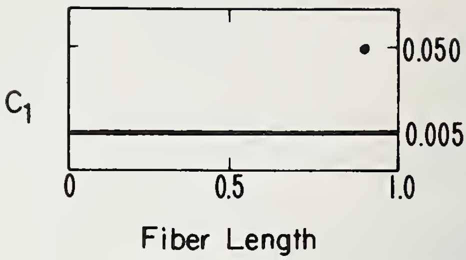
Run 660 illustrates the effect on L_2 of a point defect involving increased capture fraction. An example is a small crack or bubble which reflects radiation in the back direction. In practice a defect of this sort would occur in conjunction with other loss mechanisms. The C_1 effects shown are similar to and slightly larger than corresponding S_1 defects of a comparable relative magnitude change. Runs 661 and figure 11 show the effect of the location of the C_1 defect as a function of fiber length.

RUN: 661

VARIABLE: C_1

$C_1 = 0.005 \quad n \neq 95$

$C_1 = 0.050 \quad n = 95$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005 to 0.050
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.151587 dB
L_2	Least-sq. attn.	=	1.881290 dB
r	Corr. coeff. for L_2	=	0.554970
L_1-L_2		=	0.270297 dB
L_4	Piecewise attn.	=	2.151587 dB
L_1-L_4		=	0.0
L_3	Two-point attn.	=	2.151587 dB
L_1-L_3		=	0.0

REMARKS:

See run 660.

Run 661 corresponds to reversing the fiber end for end. In this case the average value of L_2 in the two directions is equal to L_1.

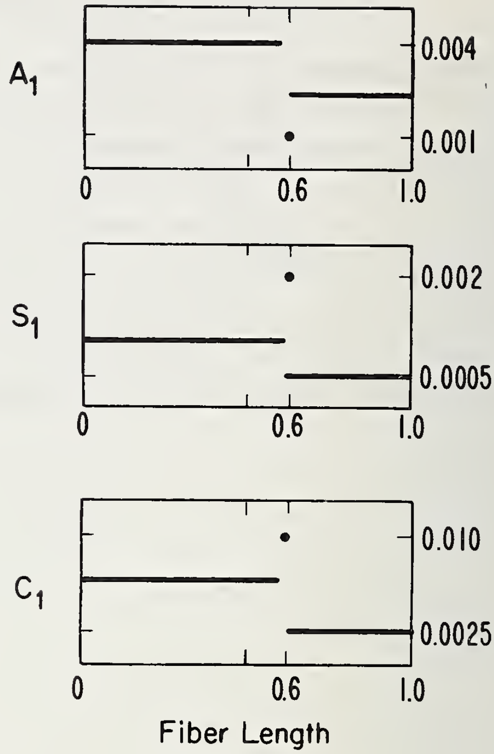
4.2 Loss Discontinuities

The examples in this section simulate the condition in which different fiber parameters can be assigned to two distinct regions of the fiber. Two different fibers joined together at a splice or connector would give a similar response. The difference in loss and scattering parameters used for illustration purposes are generally exagerated over the values normally encountered in practice. This was done in order to more clearly observe the effects on fiber attenuation values. Representative backscatter responses have been shown in figures 3 and 4. Many of the results obtained in the examples here can be anticipated from the discussion of section 3.4.

RUN: 650

PARAMETER VALUES:

A_1	= 0.004	$0 \leq n \leq 59$
A_1	= 0.001	$n = 60$
A_1	= 0.002	$61 \leq n \leq 99$
S_1	= 0.001	$0 \leq n \leq 59$
S_1	= 0.002	$n = 60$
S_1	= 0.0005	$61 \leq n \leq 99$
C_1	= 0.005	$0 \leq n \leq 59$
C_1	= 0.010	$n = 60$
C_1	= 0.0025	$61 \leq n \leq 99$
K	= 100	



COMPUTED RESULTS:

L_1	=	1.724346 dB
L_2	=	5.992639 dB
r	=	0.8010197
L_1-L_2	=	-4.268293 dB
L_4	=	4.734645 dB
L_1-L_4	=	-3.010299 dB
L_3	=	4.734645 dB
L_1-L_3	=	-3.010299 dB

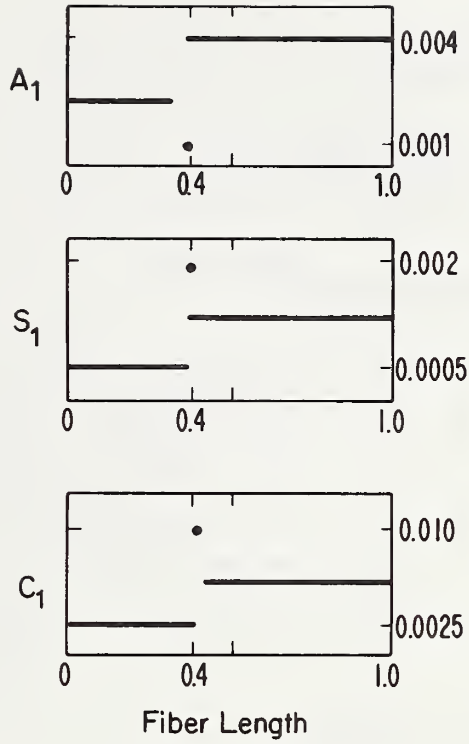
REMARKS:

Runs 650 and 651 are complementary; they correspond to reversing the fiber end for end. From a comparison of these two runs we observe that the least-squares average attenuation obtained with the ends interchanged is $\overline{L}_2$ = 1.776 dB. This is rather surprising agreement with L_1 = 1.724 dB, considering the extreme pathology of the overall fiber. Other examples in this series exhibit this same close association. As expected, L_3 and L_4 yield correct values of attenuation only when averaged with the ends interchanged. Data is plotted in figure 7.

RUN: 651

PARAMETER VALUES:

A_1 = 0.002 $0 \le n \le 38$
A_1 = 0.001 $n = 39$
A_1 = 0.004 $40 \le n \le 99$
S_1 = 0.0005 $0 \le n \le 38$
S_1 = 0.002 $n = 39$
S_1 = 0.001 $40 \le n \le 99$
C_1 = 0.0025 $0 \le n \le 38$
C_1 = 0.010 $n = 39$
C_1 = 0.005 $40 \le n \le 99$
K = 100



COMPUTED RESULTS:

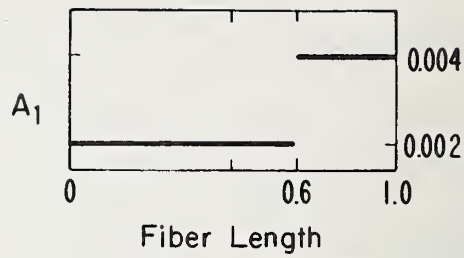
L_1 = 1.724346 dB
L_2 = -2.440969 dB
r = 0.3702988
L_1-L_2 = 4.165315 dB
L_4 = 1.285854 dB
L_1-L_4 = 0.438492 dB
L_3 = 1.285854 dB
L_1-L_3 = 0.438492 dB

REMARKS:

The least-squares value of attenuation is negative here, indicating that a positive exponential is the best fit to the backscatter data. This effect is due to the large values of scattering loss and capture fraction near the output end of the fiber. See run 650, and figure 8. Note the apparent gain at the discontinuity.

RUN: 656

VARIABLE: A_1



$A_1 = 0.002 \quad 0 \leq n \leq 59$

$A_1 = 0.004 \quad 60 \leq n \leq 99$

$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.002 to 0.004
A_2	Back absorption loss	=	0.002 to 0.004
A_3	Total forward loss	=	0.003 to 0.005
A_4	Total back loss	=	0.003 to 0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

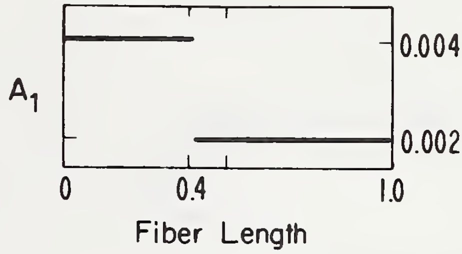
L_1	Direct attn.	=	1.634001 dB
L_2	Least-sq. attn.	=	1.593529 dB
r	Corr. coeff. for L_2	=	0.9841132
L_1-L_2		=	0.040472 dB
L_4	Piecewise attn.	=	1.634000
L_1-L_4		=	0.000001 dB
L_3	Two-point attn.	=	1.634000 dB
L_1-L_3		=	0.000001 dB

REMARKS:

Runs 656 and 655 are complementary; they correspond to reversing the fiber end for end. We note that the least squares attenuation L_2 and correlation coefficient r are the same with the ends interchanged. This is true for all absorption loss perturbations, but is not the case for scattering or capture fraction perturbations. Also, changing the absorption loss by a factor of two has a much smaller effect on backscatter attenuations than a corresponding change in scattering loss or capture fraction (compare with runs 657 and 660). The piecewise attenuation L_4 and two-point attenuation L_3 values are correct.

RUN: 655

VARIABLE: A_1



$A_1 = 0.004 \quad 0 \leq n \leq 39$
$A_1 = 0.002 \quad 40 \leq n \leq 99$
$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.002 to 0.004
A_2	Back absorption loss	=	0.002 to 0.004
A_3	Total forward loss	=	0.003 to 0.005
A_4	Total back loss	=	0.003 to 0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

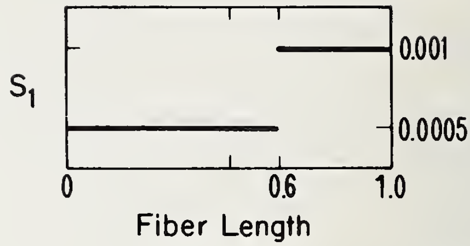
L_1	Direct attn.	=	1.634001 dB
L_2	Least-sq. attn.	=	1.593529 dB
r	Corr. coeff. for L_2	=	0.9841132
L_1-L_2		=	0.040472 dB
L_4	Piecewise attn.	=	1.634000
L_1-L_4		=	0.000001 dB
L_3	Two-point attn.	=	1.634000 dB
L_1-L_3		=	0.000001 dB

REMARKS:

See run 656 for discussion.

RUN: 657

VARIABLE: S_1



$S_1 = 0.0005 \quad 0 \leq n \leq 59$

$S_1 = 0.001 \quad 60 \leq n \leq 99$

$S_2 = S_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.0045 to 0.005
A_4	Total back loss	=	0.0045 to 0.005
S_1	Forward scattering loss	=	0.0005 to 0.001
S_2	Back scattering loss	=	0.0005 to 0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.022336 dB
L_2	Least-sq. attn.	=	0.1337266 dB
r	Corr. coeff. for L_2	=	0.01012404 dB
L_1-L_2		=	1.888609 dB
L_4	Piecewise attn.	=	0.5171862 dB
L_1-L_4		=	1.505149 dB
L_3	Two-point attn.	=	0.5171862 dB
L_1-L_3		=	1.505149 dB

REMARKS:

Runs 657 and 658 are complementary; they correspond to reversing the fiber end for end. Scattering loss changes are seen to have a much greater effect on backscatter attenuation values than corresponding absorption loss changes. Also, increased scattering loss near the output end of the fiber decreases all of the backscatter-derived attenuations, L_2, L_3, and L_4. The average least-squares attenuation $\overline{L}_2$ with the fiber ends interchanged is 2.145956 dB, which as in other examples of this kind, is in fair agreement with the direct attenuation considering the magnitude of the S_1 changes. Also, L_3 and L_4 yield correct values only when averaged with the ends interchanged.

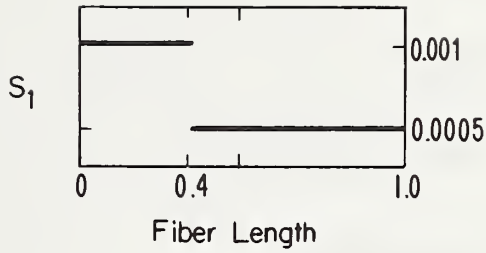
RUN: 658

VARIABLE: S_1

$S_1 = 0.001 \quad 0 \leq n \leq 39$

$S_1 = 0.0005 \quad 40 \leq n \leq 99$

$S_2 = S_1$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.0045 to 0.005
A_4	Total back loss	=	0.0045 to 0.005
S_1	Forward scattering loss	=	0.0005 to 0.001
S_2	Back scattering loss	=	0.0005 to 0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.022336 dB
L_2	Least-sq. attn.	=	4.158186 dB
r	Corr. coeff. for L_2	=	0.9039554 dB
L_1-L_2		=	-2.135850 dB
L_4	Piecewise attn.	=	3.527486 dB
L_1-L_4		=	-1.505150 dB
L_3	Two-point attn.	=	3.527486 dB
L_1-L_3		=	-1.505150 dB

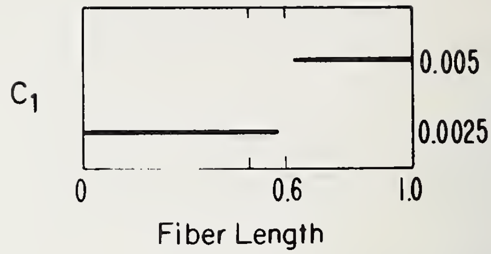
REMARKS:

See run 657.

RUN: 660

VARIABLE: C_1

$C_1 = 0.0025 \quad 0 \leq n \leq 59$
$C_1 = 0.005 \quad 60 \leq n \leq 99$



PARAMETER VALUES:

A_1	Forward absorption loss	= 0.004
A_2	Back absorption loss	= 0.004
A_3	Total forward loss	= 0.005
A_4	Total back loss	= 0.005
S_1	Forward scattering loss	= 0.001
S_2	Back scattering loss	= 0.001
C_1	Capture fraction	= 0.0025 to 0.005
K	Number of points	= 100

COMPUTED RESULTS:

L_1	Direct attn.	= 2.151587 dB
L_2	Least-sq. attn.	= 0.005630 dB
r	Corr. coeff. for L_2	= 0.000017 dB
L_1-L_2		= -2.145957 dB
L_4	Piecewise attn.	= 0.646437 dB
L_1-L_4		= -1.499519 dB
L_3	Two-point attn.	= 0.646437 dB
L_1-L_3		= -1.499519 dB

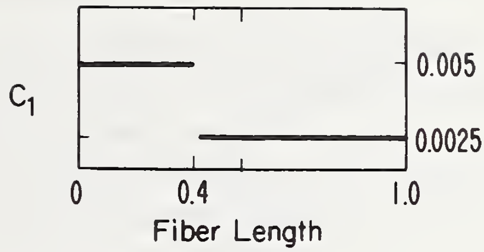
REMARKS:

Runs 660 and 661 are complementary; they correspond to reversing the fiber end for end. The effect of capture fraction changes on backscatter results is very similar to scattering loss changes (in this connection see figures 10 and 11). There is one difference, however. The average (in decibels) least-square attenuation with the fiber ends interchanged, $\overline{L}_2$, is exactly equal to the direct attenuation L_1 (also see runs 660 and 661). This is not true in general for perturbations involving absorption loss and scattering loss. Also, the piecewise attenuation L_3 and two-point attenuation L_4 yield correct values only when averaged with the ends interchanged.

RUN: 659

VARIABLE: C_1

C_1 = 0.005 $0 \leq n \leq 39$
C_1 = 0.0025 $40 \leq n \leq 99$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.0025 to 0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.151587 dB
L_2	Least-sq. attn.	=	4.297544 dB
r	Corr. coeff. for L_2	=	0.9116329 dB
L_1-L_2		=	-2.145957 dB
L_4	Piecewise attn.	=	3.656737 dB
L_1-L_4		=	-1.505150 dB
L_3	Two-point attn.	=	3.656737 dB
L_1-L_3		=	-1.505150 dB

REMARKS:

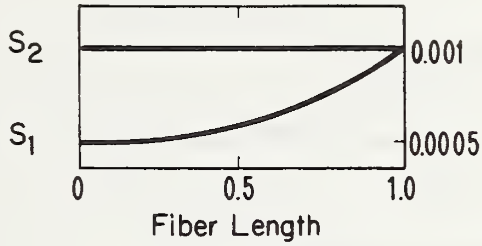
See run 660 for discussion. This type of splice cannot be realized physically without increased radiation loss which in our model would correspond to increased A_1 values at the interface region.

4.3 Distributed Loss Effects

Distributed effects in our context are defined to be slowly varying changes in absorption, scattering or capture fraction as a function of distance along the fiber. These effects have two origins. The physical properties of the fiber may change due to the way it was drawn, or the scattering and absorption properties may change due to mode coupling effects as the pulse propagates down the fiber. Both of these effects are modeled here.

RUN: 302

VARIABLE: S_1



$S_1 = 0.0005 \ \exp [.00701\ n]$

$S_2 = 0.001$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.0045 to 0.005
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.0005 to 0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

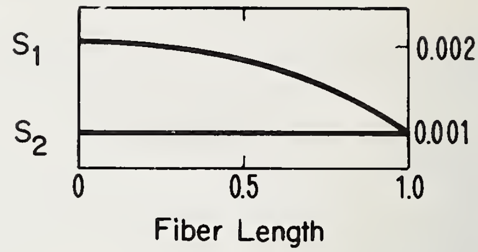
L_1	Direct attn.	=	2.031732 dB
L_2	Least-sq. attn.	=	0.5853181 dB
r	Corr. coeff. for L_2	=	0.9994468 dB
L_1-L_2		=	-1.4464139 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	0.5853181 dB
L_1-L_4		=	-1.4452224 dB

REMARKS:

This run simulates the case where the pulse is launched into a multimode fiber in which most of the energy initially is carried in low order (and low scattering loss) modes. Near the fiber end the energy has reached its final distribution where we assume that $S_1 = S_2$. As in other examples where S_1 is not constant, we note that drastic departures are introduced into the backscatter-derived attenuation values, even though the scattering loss is a small fraction of the total loss. This type of effect yields low values for L_2, and L_4. Note also that the correlation coefficient is near unity, even though attenuation errors are very large. This latter result is characteristic of distributed defects.

RUN: 311

VARIABLE: S_1



S_1 = .002exp [-.00701 n]
S_2 = .001

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005 to 0.006
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001 to 0.002
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

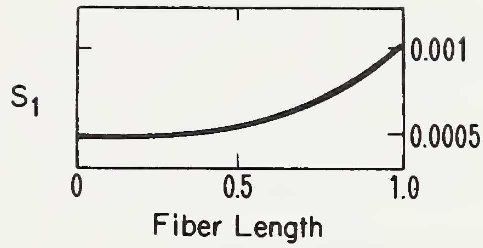
L_1	Direct attn.	=	2.342053 dB
L_2	Least-sq. attn.	=	3.842431 dB
r	Corr. coeff. for L_2	=	0.9997911 dB
L_1-L_2		=	-1.5003780 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	3.847202 dB
L_1-L_3		=	-1.505149 dB

REMARKS:

This run is similar to run 302 except here the simulation applies to the case where the pulse is launched into relatively high order (and high scattering loss) modes, with the final scattering value the same as before. Not surprisingly, the errors in L_2 and L_4 are opposite in sign.

RUN: 310

VARIABLE: S_1



$S_1 = .005 \exp [.007001\, n]$

$S_2 = S_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.0045 to 0.005
A_4	Total back loss	=	0.0045 to 0.005
S_1	Forward scattering loss	=	0.0005 to 0.001
S_2	Back scattering loss	=	0.0005 to 0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.031732 dB
L_2	Least-sq. attn.	=	-0.5241989 dB
r	Corr. coeff. for L_2	=	0.9972125 dB
L_1-L_2		=	2.555930 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	-0.526582 dB
L_1-L_3		=	2.558314 dB

REMARKS:

This run simulates the case where the intrinsic scattering loss increases toward the output end of the fiber. We note that, with the parameters chosen, a positive exponential is the best fit to the backscatter signal which results in a negative value for L_2. Runs 310 and 303 are complementary; they correspond to reversing the fiber end for end. As we have observed before, the average value of the two-point attenuation $\overline{L}_3$ when the ends are interchanged yields the correct attenuation. The average value for the least-squares attenuation in runs 310 and 303 is $\overline{L}_2$ = 2.0293489 dB, which is approximately correct.

RUN: 303

VARIABLE: S_1

S_1 = .001 exp [-.00701 n]
$S_2 = S_1$

PARAMETER VALUES:

A_1	Forward absorption loss	= 0.004
A_2	Back absorption loss	= 0.004
A_3	Total forward loss	= 0.0045 to 0.005
A_4	Total back loss	= 0.0045 to 0.005
S_1	Forward scattering loss	= 0.0005 to 0.001
S_2	Back scattering loss	= 0.0005 to 0.001
C_1	Capture fraction	= 0.005
K	Number of points	= 100

COMPUTED RESULTS:

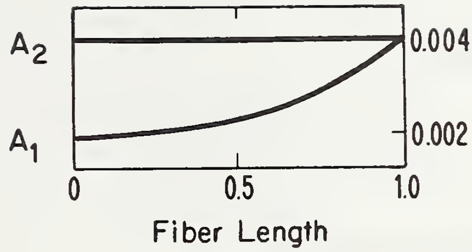
L_1	Direct attn.	= 2.031732 dB
L_2	Least-sq. attn.	= 3.534499 dB
r	Corr. coeff. for L_2	= 0.9999385 dB
L_1-L_2		= -1.502767 dB
L_4	Piecewise attn.	= N.A.
L_1-L_4		= N.A.
L_3	Two-point attn.	= 3.536882 dB
L_1-L_3		= -1.505150 dB

REMARKS:

See run 310.

RUN: 315

VARIABLE: A_1



A_1 = .002 exp [.00701 n]
A_2 = .004

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.002 to 0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.003 to 0.005
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

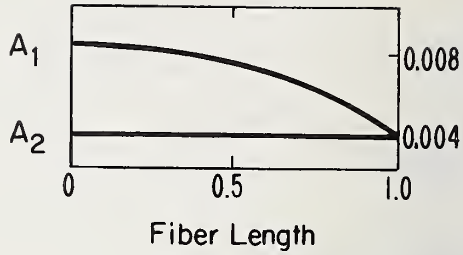
L_1	Direct attn.	=	1.671574 dB
L_2	Least-sq. attn.	=	1.906803 dB
r	Corr. coeff. for L_2	=	0.9991511 dB
L_1-L_2		=	-0.235229 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	1.911580 dB
L_1-L_3		=	-0.240006 dB

REMARKS:

This run simulates the case where the pulse is launched into a multimode fiber in which most of the energy initially is carried in low order (and low absorption loss) modes. Near the fiber end the energy has reached its equilibrium distribution where we assume that $A_1 = A_2$. Even though the absorption is the dominant component of the total loss, the effect of absorption changes on backscatter values is much smaller than comparable scattering loss changes. This type of effect yields high values for L_2 and L_3 with a near-unity correlation coefficient.

RUN: 316

VARIABLE: A_1



A_1 = .008 exp [-.00701 n]

A_2 = .004

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004 to 0.008
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005 to 0.009
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

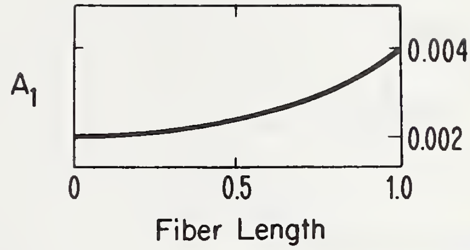
L_1	Direct attn.	=	2.914955 dB
L_2	Least-sq. attn.	=	2.523689 dB
r	Corr. coeff. for L_2	=	0.9980565 dB
L_1-L_2		=	0.391266 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	2.53327 dB
L_1-L_3		=	0.381685 dB

REMARKS:

This run is similar to run 315 except here the simulation applies to the case where the pulse is launched into relatively high order (and high absorption loss) modes, with the final absorption loss as before. The backscatter attenuations L_2 and L_3 are too low in this case.

RUN: 306

VARIABLE: A_1



A_1 = .002 exp [.00701 n]

$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.002 to 0.004
A_2	Back absorption loss	=	0.002 to 0.004
A_3	Total forward loss	=	0.003 to 0.005
A_4	Total back loss	=	0.003 to 0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

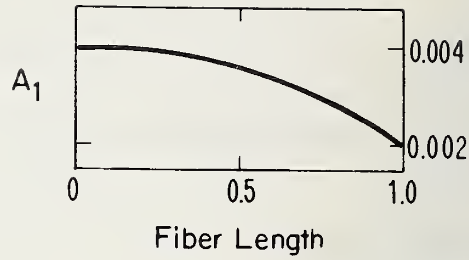
L_1	Direct attn.	=	1.671574 dB
L_2	Least-sq. attn.	=	1.662020 dB
r	Corr. coeff. for L_2	=	0.9955431 dB
L_1-L_2		=	0.0095540 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	1.671573 dB
L_1-L_3		=	0.000001 dB

REMARKS:

This run simulates the case where the intrinsic absorption loss increases toward the output end of the fiber. No large errors are encountered with this type of perturbation. Runs 306 and 307 are complementary; they correspond to reversing the fiber end for end. The least squares attenuation L_2 is the same for both cases, and both are slightly low. The two-point attenuation L_3 yields the correct value in each case.

RUN: 307

VARIABLE: A_1



$A_1 = .004 \exp[-.00701\ n]$

$A_2 = A_1$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.002 to 0.004
A_2	Back absorption loss	=	0.002 to 0.004
A_3	Total forward loss	=	0.003 to 0.004
A_4	Total back loss	=	0.003 to 0.004
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

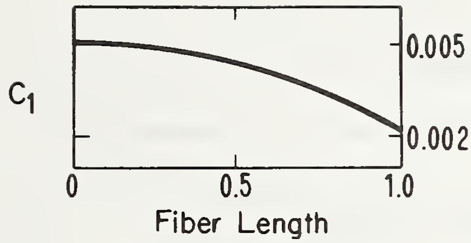
L_1	Direct attn.	=	1.671573 dB
L_2	Least-sq. attn.	=	1.662020 dB
r	Corr. coeff. for L_2	=	0.9955432 dB
L_1-L_2		=	0.0095530 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	1.671573 dB
L_1-L_3		=	0.0

REMARKS:

See run 306.

RUN: 800

VARIABLE: C_1



C_1 = 0.005 exp [-.00701 n]

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.0025 to 0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.151587 dB
L_2	Least-sq. attn.	=	3.656738 dB
r	Corr. coeff. for L_2	=	1.000000 dB
L_1-L_2		=	-1.505151 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	3.656737 dB
L_1-L_3		=	-1.505149 dB

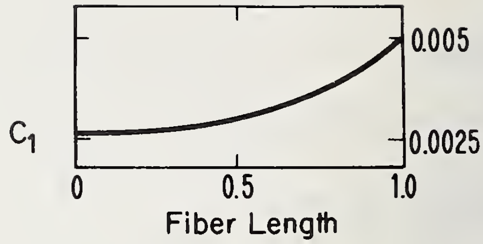
REMARKS:

This run simulates the case where the intrinsic capture fraction is lengh dependent. Variations in C_1 produce errors in L_2 and L_3 which are very similar to those produced by S_1 changes. That is, the backscatter-derived attenuations are very sensitive to these changes. Runs 800 and 801 are complementary; they correspond to reversing the fiber end for end. The average value of $\bar{L}_2$, and $\bar{L}_3$ when the ends are interchanged agree exactly with the direct attenuation L_1.

RUN: 801

VARIABLE: C_1

$$C_1 = .0025 \exp [.00701\ n]$$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.0025 to 0.005
K	Number of points	=	100

COMPUTED RESULTS:

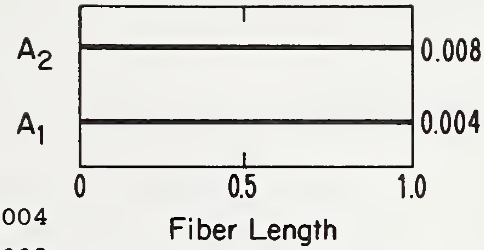
L_1	Direct attn.	=	2.151587 dB
L_2	Least-sq. attn.	=	0.646437 dB
r	Corr. coeff. for L_2	=	1.000009 dB
L_1-L_2		=	1.505149 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	0.646437 dB
L_1-L_3		=	1.505149 dB

REMARKS:

See run 800.

RUN: 326

VARIABLE: $A_1 \neq A_2$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.008
A_3	Total forward loss	=	0.005
A_4	Total back loss	=	0.009
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

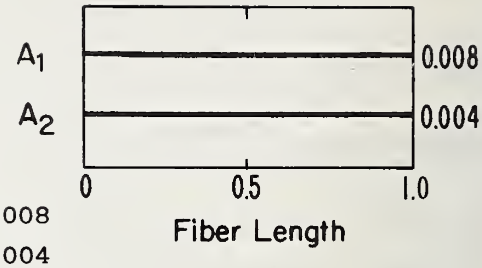
L_1	Direct attn.	=	2.151587 dB
L_2	Least-sq. attn.	=	3.014078 dB
r	Corr. coeff. for L_2	=	1.000000 dB
L_1-L_2		=	-0.862500 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	3.014078 dB
L_1-L_3		=	-0.862500 dB

REMARKS:

In this example the absorption loss in the forward direction is not equal to the reverse direction due to different modal energy distributions. We may conclude from an examination of runs 326 and 327 that both backscatter-derived attenuation values L_2 and L_4 give the arithmetic mean in decibels of the forward and back direct attenuation. That is, both L_2 and L_4 depend only on the total round trip loss, independent of interchange of forward and reverse absorption components. These results are to be expected from the defining equations given section 3. Also a unity correlation coefficient does not insure good agreement of L_1 and L_2.

RUN: 327

VARIABLE: $A_1 \neq A_2$



PARAMETER VALUES:

A_1	Forward absorption loss	=	0.008
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.009
A_4	Total back loss	=	0.005
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.001
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

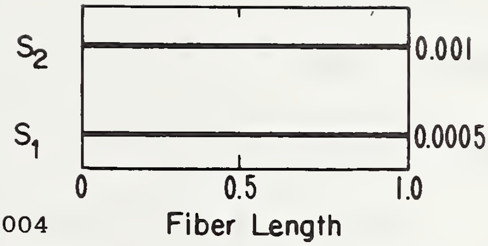
L_1	Direct attn.	=	3.876569 dB
L_2	Least-sq. attn.	=	3.014078 dB
r	Corr. coeff. for L_2	=	1.000000 dB
L_1-L_2		=	0.862491 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	3.014078 dB
L_1-L_3		=	0.862491 dB

REMARKS:

See run 326.

RUN: 312

VARIABLE: $S_1 \neq S_2$



PARAMETER VALUES:

A_1	Forward absorption loss	= 0.004
A_2	Back absorption loss	= 0.004
A_3	Total forward loss	= 0.0045
A_4	Total back loss	= 0.005
S_1	Forward scattering loss	= 0.0005
S_2	Back scattering loss	= 0.001
C_1	Capture fraction	= 0.005
K	Number of points	= 100

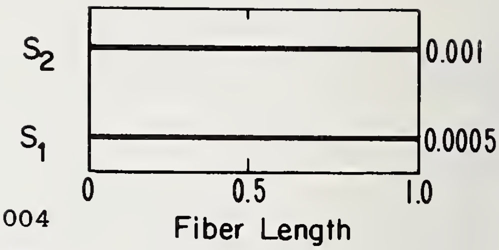
COMPUTED RESULTS:

L_1	Direct attn.	= 1.936531 dB
L_2	Least-sq. attn.	= 2.044060 dB
r	Corr. coeff. for L_2	= 1.000001 dB
L_1-L_2		= -0.107529 dB
L_4	Piecewise attn.	= N.A.
L_1-L_4		= N.A.
L_3	Two-point attn.	= 2.044059 dB
L_1-L_3		= -0.107528 dB

REMARKS:

In this example the scattering loss in the forward direction is not equal to the scattering loss in the reverse direction which could possibly be due to different modal energy distributions. By comparison with run 313 we see that L_3 is equal to L_2 and both depend only on the round trip loss, independent of interchange of forward and reverse scattering components. The unity correlation coefficient does not insure good agreement of L_1 and L_2.

RUN: 313



VARIABLE: $S_1 \neq S_2$

PARAMETER VALUES:

A_1	Forward absorption loss	=	0.004
A_2	Back absorption loss	=	0.004
A_3	Total forward loss	=	0.005
A_4	Total back loss	=	0.0045
S_1	Forward scattering loss	=	0.001
S_2	Back scattering loss	=	0.0005
C_1	Capture fraction	=	0.005
K	Number of points	=	100

COMPUTED RESULTS:

L_1	Direct attn.	=	2.151587 dB
L_2	Least-sq. attn.	=	2.044059 dB
r	Corr. coeff. for L_2	=	1.000001 dB
L_1-L_2		=	0.107528 dB
L_4	Piecewise attn.	=	N.A.
L_1-L_4		=	N.A.
L_3	Two-point attn.	=	2.044059 dB
L_1-L_3		=	0.107528 dB

REMARKS:

See run 312.

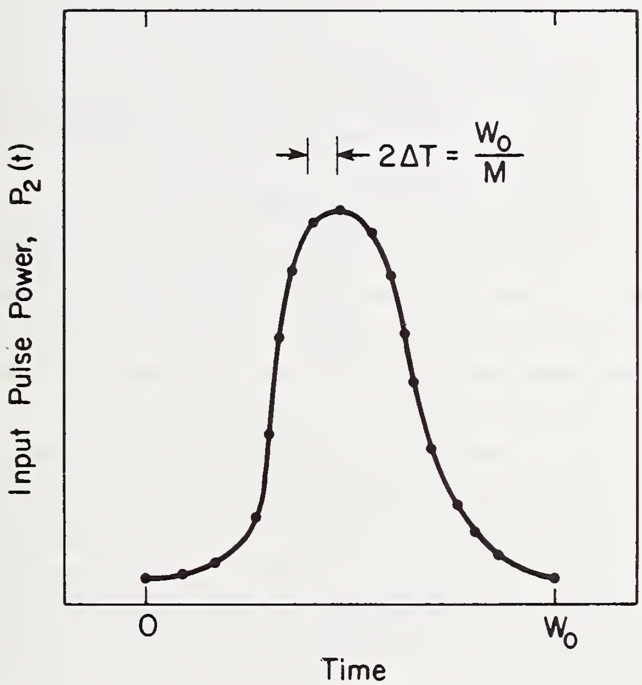


Figure 12. Temporal dependence of the input pulse considered in section 5. The pulse is truncated so that it extends from $t=0$ to $t=W_o$. The uniformly spaced time intervals are of duration $2\Delta T = W_o/M$. The pulse propagates in the sampled waveguide labeled in figure 1.

5. EXTENSION OF ANALYSIS TO PULSES OF ARBITRARY SHAPE

Up to this point we have considered the response of a discrete-waveguide model to an input pulse whose temporal power dependence is approximated by a delta function. In this section we will indicate how the present analysis can be extended to a more general input pulse shape. The results of the foregoing computer modeling will not be altered significantly so long as the pulse length expressed in meters is small compared to the regions of the waveguide over which the scattering and loss properties vary appreciably. Nevertheless, it is desirable from an experimental point of view to obtain as much energy in the pulse as possible, and this often is practical only for a longer pulse. We will therefore give a few examples of the effect of a non-zero width pulse on the backscatter response.

In order to simplify the following analysis, we will consider a discrete pulse which is sampled at twice the time interval previously defined in connection with the waveguide of figure 6. This factor of two comes about as a result of the fact that the backscatter signal must travel down the fiber and return, while we have taken the unit of time ΔT to be the transit time across an element in one direction only.

Referring now to figure 3, we have a input pulse $P_i(t)$ whose amplitude is sampled at intervals $2\Delta T = 2X_o/vk$ where v is again the group velocity of the pulse in the fiber, X_o the assumed fiber length and k the number of scattering elements in the waveguide model. The input pulse is taken to have M intervals, that is we consider $P_i(t)$ to be composed of a sum of discrete pulses of energy $P_i(2m\Delta T)2\Delta T$, with $0 \leq m \leq M$.

We will now examine the response of our discrete fiber to this sampled pulse. In section 3 it was shown that the response of our sampled fiber to an impulse input $P_i(t-t_n) = \delta(t-t_n)$ at time t_n is given by the normalized quantity $E_b\ (t-t_n)$. Since we are considering a linear system, the response to the input $P_i(t_n)2\Delta T\delta(t-t_n)$ is $P_i(t_n)2\Delta TE_b(t-t_n)$ and the overall output backscatter power of the fiber as a function of time is given by

$$P_b(t) = \sum_r P_i(tr)E_b(t-t_r) \qquad (5\text{-}1)$$

Making the substition $t-t_r = t'$ and using the fact that the time intervals are digitized, $t = 2m\Delta T$, and $t' = 2n\Delta T$. eq (5-1) becomes

$$P_b(2m\Delta T) = \sum_{n=o}^{m} P_i[2\Delta T(m-n)]\ E_b(2\Delta Tn) \qquad (5\text{-}2)$$

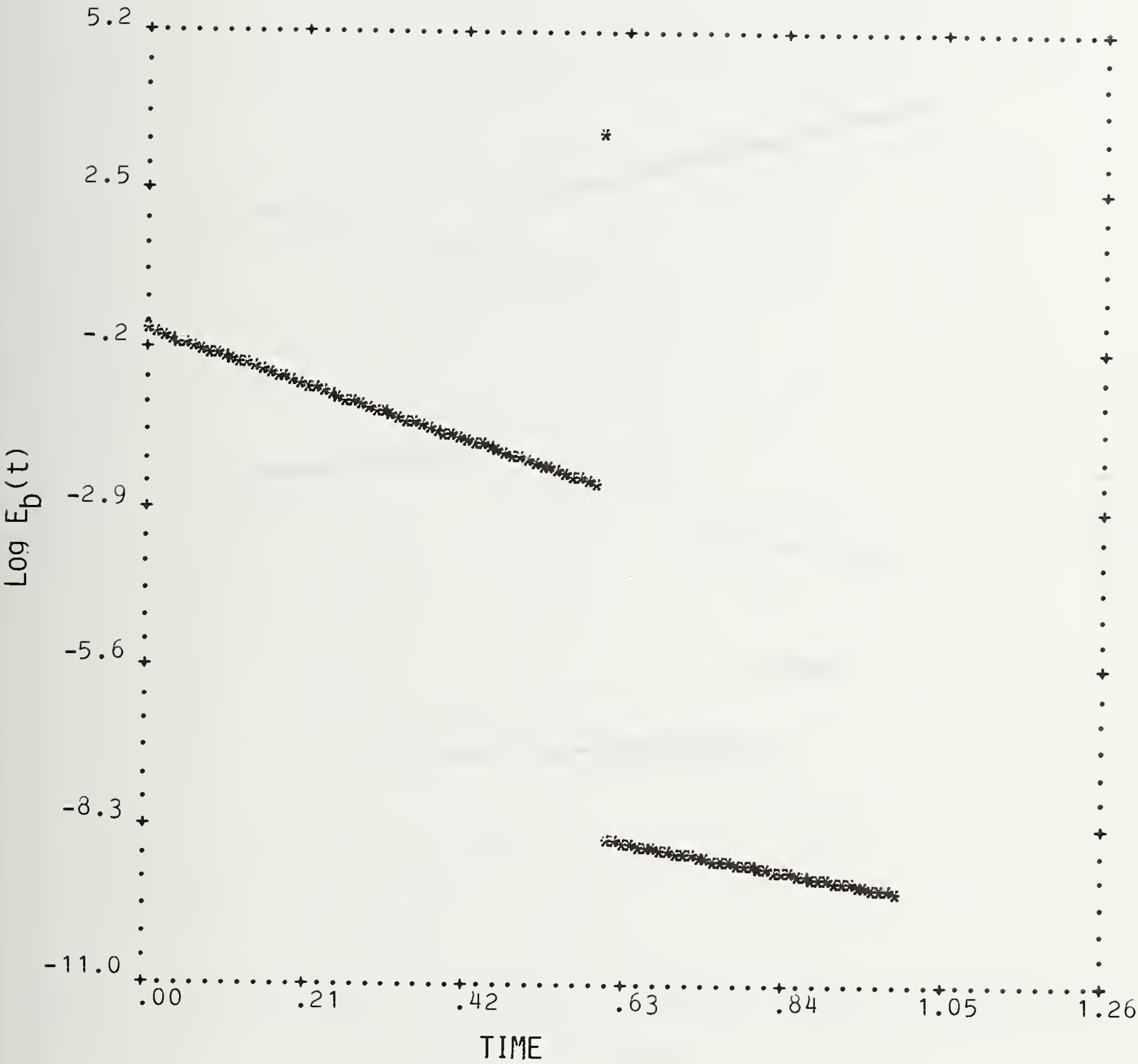


Figure 13. The impulse response function for a fiber with three loss regions. The logarithm of the backscatter power is plotted as a function of time, with the response normalized to unity time.

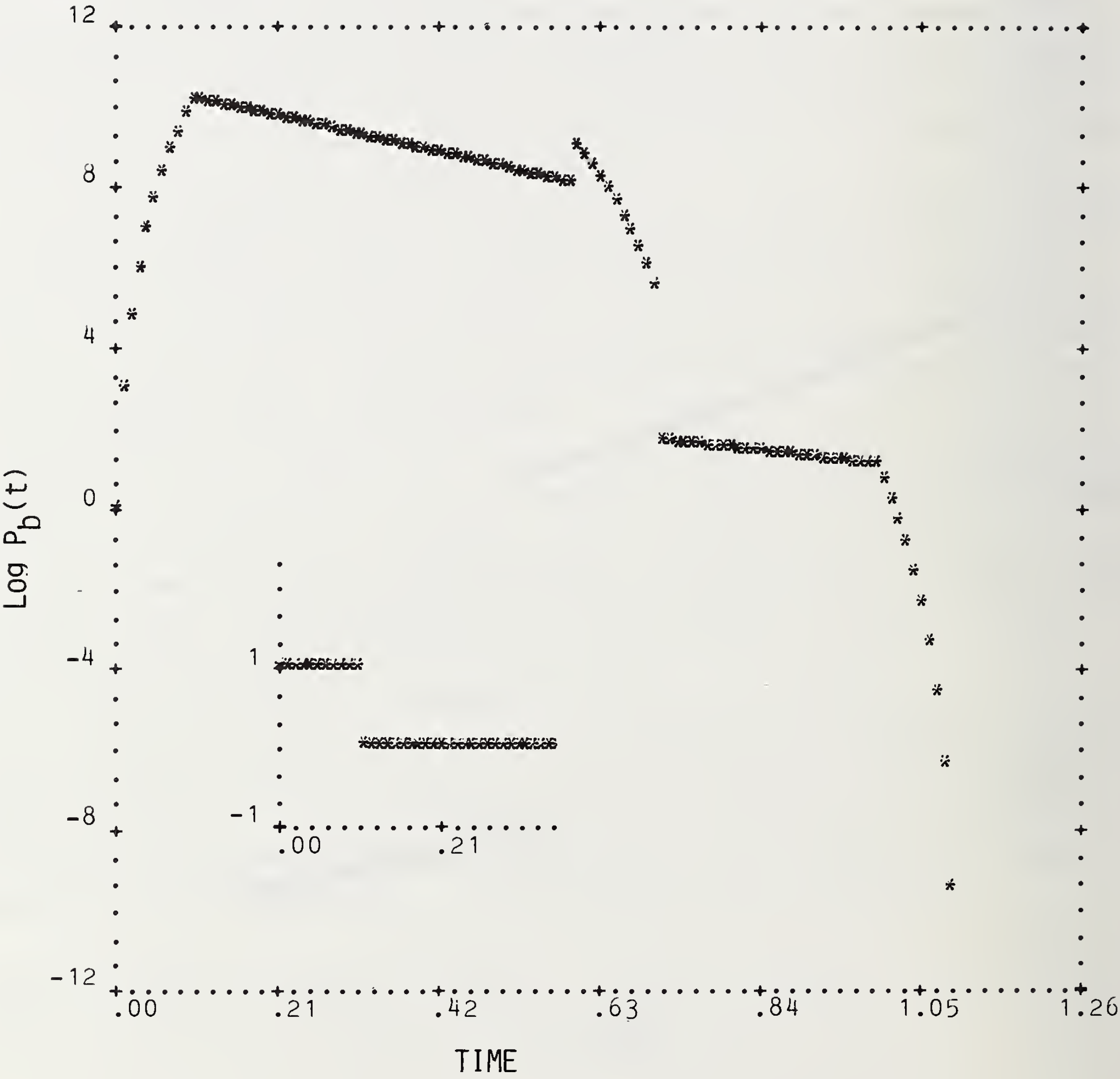


Figure 14 The logarithm of backscatter power as a function of time for a square pulse input (inset) with the impulse response given in figure 13.

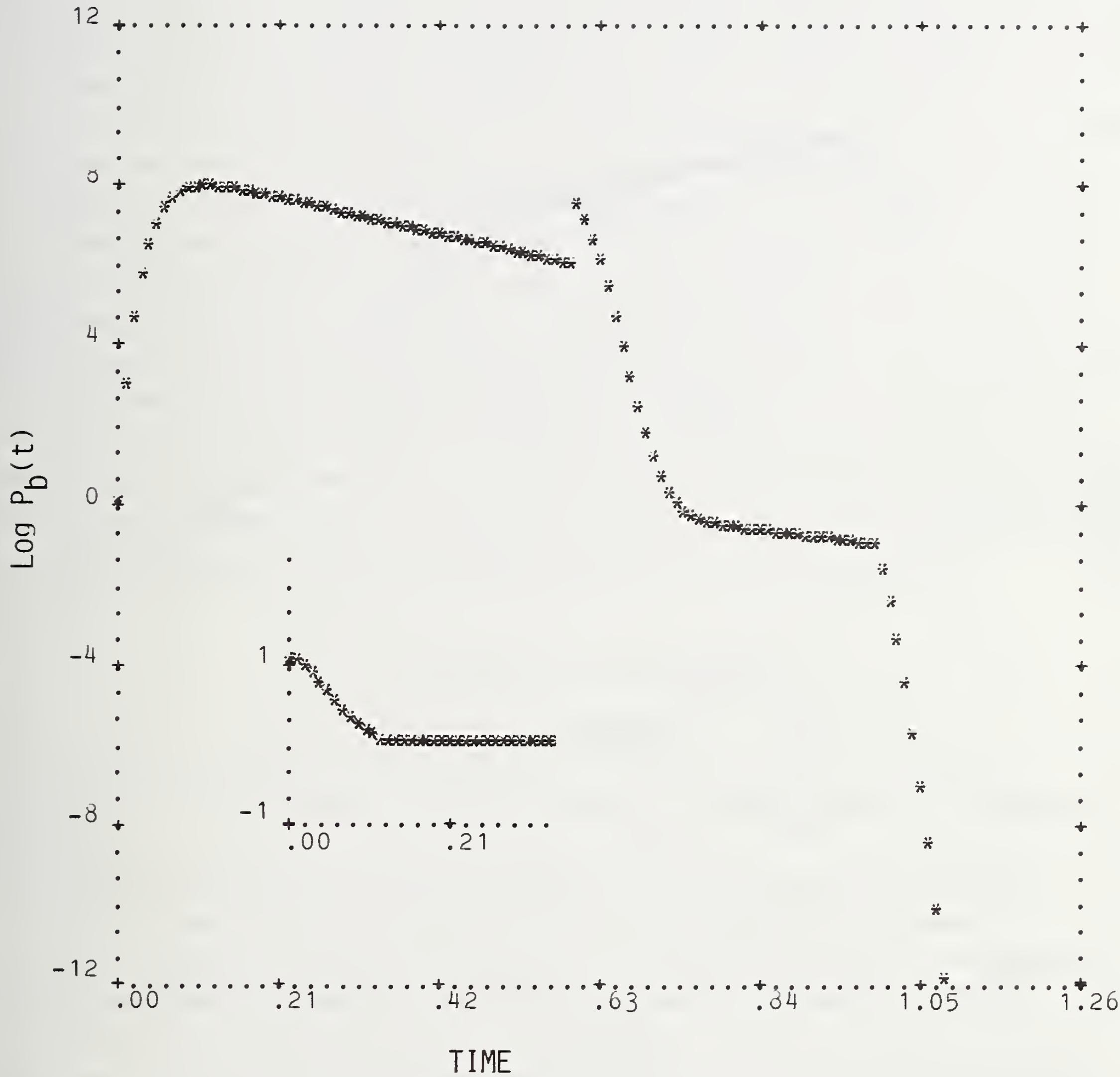


Figure 15. The logarithm of backscatter power as a function of time for a pulse with Gaussian-shaped trailing edge (inset). The impulse response function is given in figure 13.

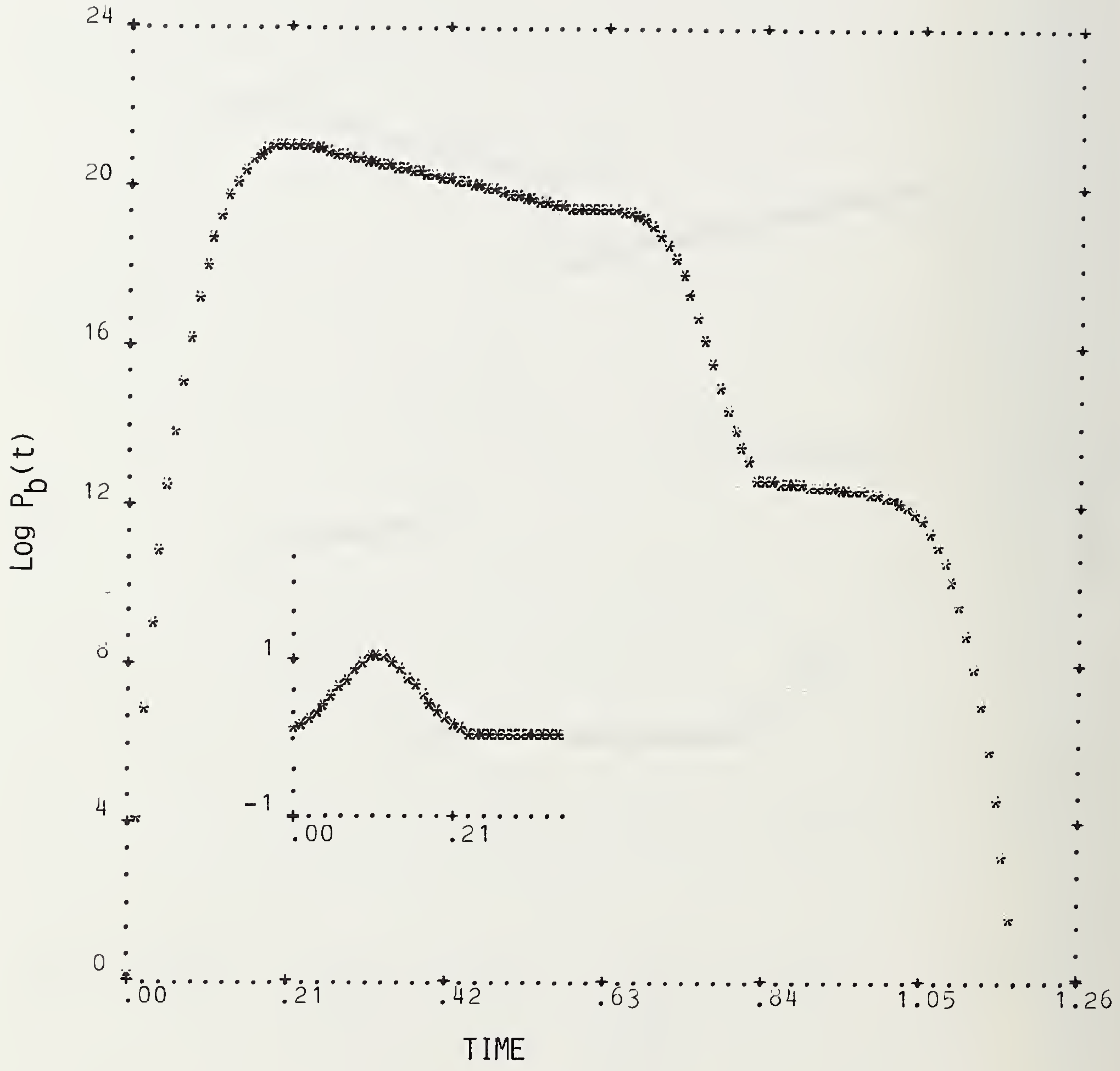


Figure 16. The logarithm of backscatter power as a function of time for a Gaussian-shaped input pulse (inset). The impulse response function is given in figure 4.

where the summation is taken over all non-vanishing terms as indicated. With the understanding that each time interval is of duration $2\Delta T$, we have finally

$$P_b(m) = \sum_{n=o}^{m} P_i(m-n)\, E_b(n) \qquad (5\text{-}3)$$

Figures 14, 15, 16 and 17 show the logarithm of the backscatter power, expressed in decibels, for several input pulse shapes to a fiber with three loss regions, the n=60 region consisting of a single point. Figure 14 is the impulse response function $E_b(t)$. Figure 15 shows the corresponding output power $P_b(m)$ for the same fiber excited by a square input pulse of unit height as shown in the inset of the figure. The location of the discontinuity is still obvious. Also, the optical backscatter power is increased by about 10 dB, as expected. Figure 6 shows the response to a pulse with an abrupt leading edge and Gaussian trailing edge. Here again the location of the discontinuity is evident. However, in figure 7 we see that the response to a Gaussian-shaped pulse tends to obscure the precise location of the fault as well as distort the impulse response function signature. Accurate loss measurements under such conditions require the deconvolution of $P_b(m)$ with the exciting pulse shape. While such techniques are straightforward in principle, they often produce results that are difficult to interpret when the signals are noisy. Such procedures will not be pursued here.

6. DISCUSSION OF RESULTS

The principal effects responsible for the discrepancy between the attenuation values determined from the insertion method and the backscatter methods are:

(1) Different properties of the fiber in the forward and reverse directions. This nonreciprocity can be due to a different distribution of modal energy in the two directions, or to physical properties affecting the localized numerical aperture of the fiber.

(2) Non-uniformity of loss parameters along the length of the fiber. Scattering variations particularly can produce large differences in the calculated backscatter value.

(3) Excessive pulse durations. The source pulse lengths (expressed as a length in the fiber) should be much less than the length of the region over which appreciable loss (or capture fraction changes) occur. Narrow pulses permit identification of the limits of uniform

loss regions, but at the expense of degraded SNR. The SNR is effected in two ways: the backscatter signals are proportional to pulse energy, or pulse width for constant peak power, and in addition increased electronic bandwidth is required for narrower pulses. Obviously, some kind of experimental tradeoffs are required as to input pulse width.

(4) Signal-to-noise considerations. Backscatter signals are inherently small due to the nature of the scattering involved, and SNR limitations may be the determining factor in the utility of this approach.

From the discussion of the OTDR theory and examination of sections 4 and 5, we can infer the following:

(1) In the case of reciprocal waveguides whose loss and scattering properties as well as localized capture fractions are not length dependent, we can expect the direct attenuation values to agree exactly with backscatter-derived attenuation values (ignoring SNR considerations and any non-zero width of the interrogating pulse).

(2) In cases where the fiber is uniform, but the loss properties differ in the forward and reverse directions, both the least-squares backscatter attenuation and the two-point backscatter attenuation will yield the average (in decibels) of the total attenuation (sum of absorption + scattering loss) in the two directions.

(3) Where lossy point defects are encountered and where fibers of different properties are joined, the piecewise least-squares method is preferred to a least-squares fit over the entire fiber. In such cases, the piecewise fit agrees with the insertion value only if the scattering loss and capture fraction are the same in the two regions to be fit.

(4) The two-point backscatter attenuation in some cases can agree with the insertion attenuation even if the fiber is not uniform. The conditions for equality are: the impulse response function must be known; the back/forward losses are identical; and the scattering loss and capture fractions are the same at the two measuring points. If the scattering loss-capture fraction criterion is not met, the two-point method still gives the correct value if the average (in decibels) of the attenuation values is taken from the two ends of the fiber.

(5) The correlation coefficient is not always a good indication of agreement between the least-squares and insertion attenuation values. This is graphically demonstrated in the examples of section 4.4 where distributed scattering losses as a function of length produced large L_1-L_2 differences, but correlation coefficients near

unity. However, the correlation coefficient is a good indication of agreement in cases involving reciprocal, uniform fibers where errors are introduced due to random noise.

(6) A short rise time on the exciting pulse is important in the identification of regions of differing uniform loss so that the piecewise fit method can be applied. The trailing edge of the pulse is less significant (section 5).

(7) The residuals to the least-squares fit, the backscatter signal as a function of time, and, to a lesser extent, the correlation coefficient, in combination often provide a signature which can be used as a diagnostic to identify a particular class of perturbations as well as their location. In some cases this information may be employed to judiciously pick the regions for a piecewise fit. A detailed analysis of these defect signatures will be the basis for a future NBS internal report.

(8) Departures from scattering-loss uniformity and capture fraction uniformity produce much larger L_1-L_2 discrepencies than departures from absorption-loss uniformity.

(9) The two-point backscatter method is often more accurate than a least-squares fit. In addition, the two-point method is preferable from the practical standpoint that it requires less time for an attenuation measurement. However, there is the drawback that this approach does not provide a defect signature.

7. COMPARISON WITH EXPERIMENT

The inherent accuracy of the backscatter approach for making loss determinations is difficult to assess from published experimental comparisons with insertion loss measurements [2,12,17,18]. Usually a detailed knowledge of the materials properties of the fiber in question, such as index profile, uniformity and loss characteristics, as well as the precise experimental conditions under which the probing pulse is launched, is not known. About the only conclusion which can be drawn from these comparisons is that good agreement is at least possible with some fibers under some conditions. A few of these experimental comparisons, at NBS and other laboratories, are summarized in tables II and III. In some of these examples the agreement is very good.

The data shown in table II represent preliminary results (subsequent experimental refinements have resulted in improved precision [25]). The input pulses of about 80 ns full width at half maximum, were launched under conditions where the waveguide was overfilled.

TABLE II. ATTENUATION COMPARISONS, NBS

FIBER	TYPE MEASUREMENT	ATTENUATION dB/KM	NUMBER OF MEASUREMENTS
GRADED FIBER (1365) .63 μm	BACKSCATTER (L_2)	10.21 ±0.19	7
	DIRECT (L_1)	10.41 ±0.16	3
STEP FIBER (1006) .63 μm	BACKSCATTER (L_2)	15.99 ±0.28	5
	DIRECT (L_1)	16.75 ±0.21	3
STEP (FIBER 1006) .87 μm[a]	BACKSCATTER (L_2)	13.7 ±0.4	24
	DIRECT (L_1)	15.2 ±0.3	4

[a]These measurements made by D.L. Franzen on a waveform digitizer with a laser specifically constructed for backscatter studies [16].

TABLE III. ATTENUATION COMPARISONS, OTHER LABORATORIES

LABORATORY	FIBER	(L_2) BACKSCATTER, dB/KM	(L_1) INSERTION, dB/KM	DIFFERENCE, dB/KM
CSELT[a]	STEP	5.026 ±.04	5.9	-.9
HUGHES[b]		7.9	8.2	-.3

[a]Reference [17]

[b]Reference [12]

Mode strippers were used to eliminate radiation propagating in the cladding. The scatter is indicated by the one sigma limits.

In addition to the results presented in the tables, some recent data from the CSELT group [18] show backscatter-direct loss comparisons on sixteen different fibers with an average difference of about 0.01 dB/km on fibers with nominal attenuation in the 3 to 4 dB/km range. Excellent agreement of this sort inspires confidence in the possibilities of backscatter measurements when good fibers are under test and measurement conditions are carefully controlled.

8. CONCLUSIONS

We have shown by means of computer modeling that backscatter-derived attenuation values can agree exactly with the direct attenuation values under certain ideal conditions. We have also examined a number of fiber perturbations which could be encountered in practice to upset these ideal conditions, and noted their effect. The perturbed backscatter attenuation values can be either higher or lower than those determined from direct, or insertion, methods. The precise agreement is a function of many factors; the quality of the fiber employed, location and magnitude of defects, type of waveguide excitation assumed, duration of the input pulse, signal-to-noise ratios, and the details of the backscatter data analysis.

It would appear that there are two distinct aspects relating to the problem of accurate backscatter-derived attenuation measurements. The first is the inherent quality of the fiber. Errors will be minimized if absorption loss, scattering loss and localized numerical aperture are not functions of fiber length. The second consideration involves measurement procedures. We feel that, before meaningful experimental backscatter-direct attenuation comparisons can be made, it will be necessary to establish standard measurement conditions and procedures. This is a consequence of the well known fact that absorption and scattering loss in multimode optical waveguides are both mode dependent quantities and that mode coupling produces complex and length-dependent loss characteristics. In order for attenuation results to be reproducable, and comparisons to be significant, measurements must be made under conditions that initially excite that set of modes at the input which most closely approximate the equilibrium or steady state modal

energy distribution.[2] This can be done, in principle at least, by carefully controlling launch conditions such as radiation spot size and NA. Another approach is to employ devices which can be used with fibers to simulate an equilibrium mode distribution (EMD). They are variously referred to as mode filters, mode scramblers, mode eliminators, or, the term we prefer, equilibrium mode simulators (EMS). The problems associated with EMS as well many practical arrangements, such as long pigtails and S-shaped channels, have been discussed by numerous authors [19,20,21]. These devices do not in themselves produce a steady state power distribution, but in combination with a set of standard excitation conditions they can produce an environment which approximates the desired steady state. At the present time no universally accepted EMS has been established. However, efforts are currently underway by the Electronic Industries Association (EIA), NBS, and other organizations to reach agreement on the precise definition of equilibrium mode distribution, as well as suitable EMS and other measurement procedures. If, as seems likely, EMS devices are adopted for use in conjunction with standardized direct attenuation procedures, we can expect some inherent discrepancy between this and backscatter-derived attenuation. This is a result of the fact that the OTDR signal originating from the Rayleigh scattering in a given fiber element is not launched in the back direction with the same sort of EMD conditions; rather, this signal approximates overfilling the waveguide (exciting all modes equally). As we have seen, nonreciprocal behavior of this sort produces attenuation variations.

When a consensus on EMS, EMD specifications, and measurement procedures is achieved the author intends to pursue further backscatter-direct attenuation comparisons. Based on our computer modeling and on preliminary results at this, and other laboratories, it would appear that, with modern high-quality fibers and standard techniques, good agreement is still possible between direct attenuation measurements and attenuation values obtained indirectly from backscatter signals.

[2] An equilibrium distribution may, in fact, not exist for some optical fibers with extremely small mode coupling. Fibers have been observed in which the output NA continually decreases even after two to three km, indicating that no steady state condition has been reached.

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☆U.S. GOVERNMENT PRINTING OFFICE:1980—677-096/1233

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS TN-1018	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

An Assessment of the Backscatter Technique as a Means for Estimating Loss in Optical Waveguides

5. Publication Date

February 1980

6. Performing Organization Code

7. AUTHOR(S)

B. L. Danielson

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Aerospace Guidance and Metrology Center, Newark Air Force Station, Newark, OH 43055 and
Communications Systems Ctr., U.S. Army Communications Command, Fort Monmouth, New Jersey 07703

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This technical note addresses some of the problems associated with determining the accuracy of the backscatter technique as it is applied to the estimation of attenuation in optical waveguides. The basic theoretical assumptions involved in optical time domain reflectometry are reviewed; the effect on calculated loss values resulting from a departure from these assumptions is then examined. The approach taken is to employ computer modeling of the various scattering and other loss mechanisms using the bulk material properties of optical fibers. Computer responses permit a numerical comparison between the direct (insertion) method of measuring attenuation and several methods of estimating attenuation from analysis of backscatter data. Numerous examples are given of physical effects which can produce discrepancies in attenuation values calculated from backscatter signals. Also, some experimental comparisons are made between backscatter-derived and directly measured attenuation values in step and graded-index optical waveguides. Finally, the conditions necessary for good agreement between the direct and backscatter methods are discussed and suggestions for minimizing these errors are made.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Backscattering; fiber attenuation; fiber loss; fiber scattering; optical time domain reflectometry; Rayleigh scattering.

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